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Operational Analysis of a Coupled MSR and TS System to Replace UK Highly Flexible Fossil-Fuel Generation

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Signed: Joshua Crawford Findlay Date: 24/08/18

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ABSTRACT

The UK's electricity is predominantly supplied by fossil fuel types of generation, including natural gas and to a lesser extent - coal. In recent years, the UK has seen large expansion and deployment of renewables in an effort to reduce carbon emissions and fossil fuel dependency, as well as trying to keep to EU emission targets. Be that as it may, large-scale deployment of renewables which are reliant on parameters outside of human control i.e. wind and sunlight, are not able to consistently supply electricity during peak demand periods. With no large-scale energy storage systems currently available, renewables remain to be an unreliable source of electricity generation. Current conventional nuclear power stations operate most economically at a constant power level, providing baseload electricity. It is this reason why natural gas turbines currently dominate the UK's electricity generation market, as they are far more efficient than coal plants, and can be easily controlled or turned on and off to supply a constantly varying electrical demand load throughout the country.

The purpose of this project is to combine a high-temperature molten salt nuclear reactor with molten salt thermal storage to provide fossil-free flexible load. The study focuses on modelling a coupled MSR with TS system to simulate an exact electricity generation profile to that of gas turbines within the UK. Electrical generation data from the UK's fleet of gas turbines was taken from two days throughout the entire year where a minimal and maximum electrical demand was experienced. The data was then scaled down to simulate a normal sized power plant (1-2 GW capacity) to determine the sizes and operational characteristics of MSR and TS combined system.

ABBREVIATIONS

MSR – Molten Salt Reactor

PWR – Pressurised Water Reactor

TS – Thermal Storage

MSRE – Molten Salt Reactor Experiment

PV – Photo Voltaic

CCGT – Combined Cycle Gas Turbine

U-233 – Uranium-233

U-235 – Uranium-235

U-238 – Uranium-238

Pu-239 – Plutonium-239

SSR – Stable Salt Reactor

Hex – Heat Exchanger

AGR – Advanced Gas-cooled Reactor

(1) INTRODUCTION

1.1) The History of MSR Technology

In the 1940's nuclear technology was gaining significant interest from the U.S. Government as a form of energy production and as weapon manufacturing. This was during the period of the Second World War, political tension was very high throughout the globe. There was a race to build the first nuclear bomb between the allies and the axis powers to effectively end the war. Unbeknownst to the general American and British public, all reactors built around this time period was not for the primary reason of producing electricity, but for producing plutonium which was required for making nuclear weapons. (Archive, 2015) After the war ended in 1945 with the devastating consequences, interest in nuclear technology continued as the U.S. Government heavily funded research into different types of reactors. The U.S. Navy had a specific interest in using small compact nuclear reactors that would power their Naval vessels, essentially eliminating the necessity for frequent inland petroleum refuelling, both an inconvenient and time-consuming process. The design of the reactor chosen for the naval fleet was a pressurised water reactor (PWR), which uses water both as a neutron moderator and a primary coolant. This type of reactor when operational requires constant flow of coolant to the reactor core to prevent the core from overheating and melting down. Naval vessels have the technical advantage over land and air-based vehicles as they are always submerged in water. The sea acts as an effective infinite heat sink for their reactors, therefore the PWR was the most preferred design and gained the most interest and funding at the time. The first type of nuclear naval vessel USS Nautilus was put to sea in 1955. By 1962 the US Navy had 26 nuclear submarines operational and 30 under construction. Nuclear power had revolutionised the Navy.

The U.S. Air Force also gained interest in nuclear-powered aircraft that would eliminate the need for refuelling and could remain in the air for far longer periods of time. PWR's had already gained substantial research and development, however, the Air Force could not use them, as they simply were too large and heavy to be put on an aircraft. This is because PWR's operate at ~300°C, therefore require thick, heavy steel vessel walls and pressurisers to maintain high pressure, keeping the water in liquid state. Researchers realised that to power a turbine without high-temperature combustion chambers, the reactor would have to operate at a much higher temperature than its PWR counterpart. In 1955, the Aircraft Reactor Experiment (ARE) developed a 2.5MWth reactor that could operate at a very high temperature (up to 860°C) but at a low pressure using the fuel in the form of a melted salt. (Rosenthal, et al., 1972)

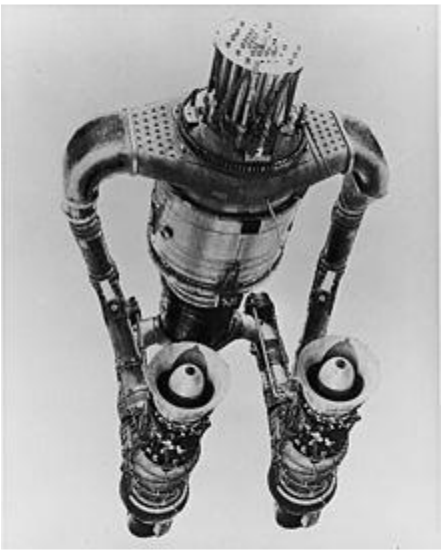


Figure 1: ARE Layout

The large temperature difference between the air and fuel made the air a technically viable heat sink source. This was the world’s first ever operational molten salt reactor, however, the project was cancelled soon after as intercontinental ballistic missiles were introduced and the need for nuclear powered bombers ended.

Several years later the MSR regained interest for commercial power generation and the Oak Ridge National Laboratory received funding to carry out the Molten Salt Reactor Experiment (MSRE). They constructed a 7.4MWth graphite moderated reactor in 1964, was operational by 1965 and ran for four years. Data was collected and analysed, and the reactor demonstrated very interesting characteristics compared to solid fuelled PWR’s, mainly that the reactor could self-control it’s reactivity without the insertion of control rods. It was also found that the salt was immune to radiation damage and the neutronics tended to agree with the researcher’s calculations prior to the experiment. The most important aspect of the experiment was that the researchers were actually able to operate an MSR for long periods of time without excessive malfunctions and time delays. (Rosenthal, et al., 1972)

Several Years later in 1972 Oakridge proposed to develop the Molten Salt Breeder Reactor, yet Government funding for the MSR program was cut in 1976 for two main reasons. Firstly the political and technical support for the program was too thin geographically. Within the U.S., only in Oak Ridge, Tennessee, was the technology really understood and appreciated. Lastly, the MSR was in competition with the liquid metal breeder program, which got an early start and had copious Government development funds being spent in many part of the U.S.. The MSR development program had gained enough insight into the technology to justify expanding the program to lead to commercial development. Although they brought their case to the U.S. Atomic Energy Commission, they could not justify the diversion of substantial funds from the Liquid Metal Fast Breeder Reactor to the competing MSR program. (MacPherson, 1985)

1.2) Problem Description

Electricity in the UK, like any other country, is distributed by the national grid that provides energy mainly for industrial, commercial and domestic use. Currently, electrical power is generated by a variety of different means. This includes thermal power plants such as nuclear, coal and gas, as well as renewables such as geothermal, solar PV, hydro and wind. Each of these sources has their own advantages and disadvantages which is discussed below. That being said, the main problem is the need for fossil-free flexible load to balance renewable generation in the future low-carbon grid.

Coal

Coal in the UK is still used but only during winter periods where electrical demand is at its highest. Coal and gas are used in power generation in the UK, yet gas burns a lot more efficiently. There are far more impurities in coal than there is in gas which produces sulphur oxides. Coal is a solid rather than being in a gaseous phase, this means that it burns more incomplete. Coal is thought to contribute massively towards global warming and air pollution with the highest concentrations of coal plants in the world being located in China. This has become an important factor restricting China's economic development and has subsequently brought a series of social problems. Clean air is a basic demand for human health and well-being, yet air pollution is still a serious problem globally, especially in fast-developing countries such as China. (Cao, et al., 2017)

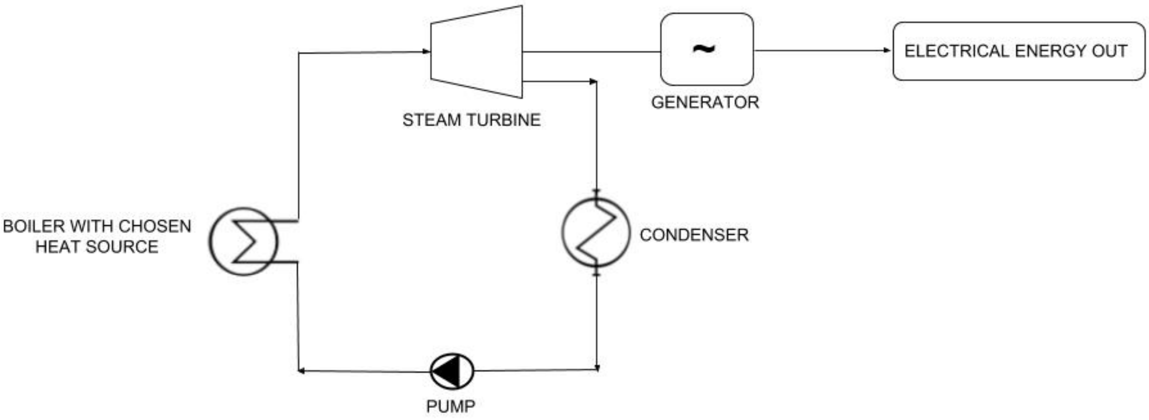


Figure 2: Thermal Power Plant Schematic Diagram

Biomass

Is similar to a thermal power plant in that it uses a steam powered turbine through use of a boiler where combustion of organic materials takes place. Biomass can be described as a ‘green’ source of energy due to the carbon that is released through combustion is said to be originally captured and utilised to grow the biomass in the first place. More studies are proving this carbon balance theory of biomass generation false as the amount of time, energy and resources required to grow the crops and transport them far exceed the energy gained from combusting it. Therefore, on a small scale basis where plants utilise organic waste materials can be beneficial to the environment but still proves unviable for large scale electricity production. (Loening, 2011)

Renewables

Renewables will have some importance in generating our electricity in the future as they require no finite resource to operate for any given length of time. Unfortunately, renewables have one major disadvantage over their thermal plant counter parts, and that is they generate electricity intermittently. This becomes a very large and real problem with high penetration rates of renewables because they only produce electricity when there are adequate levels of sun light or wind.

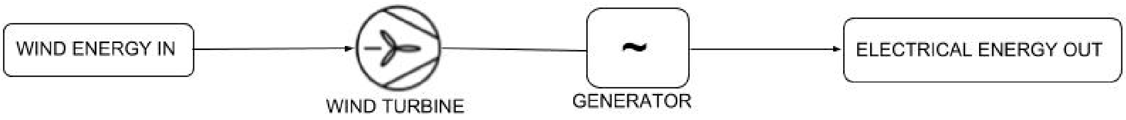


Figure 3: Wind Turbine Schematic Diagram

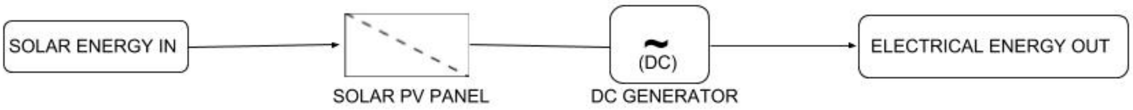


Figure 4: PV Schematic Diagram

Having a power generation source completely dependent on the weather makes renewables a highly unreliable source. This is particularly problematic due to nation-wide electricity consumption that constantly varies drastically every hour on a daily and seasonal basis as shown in figure 5:

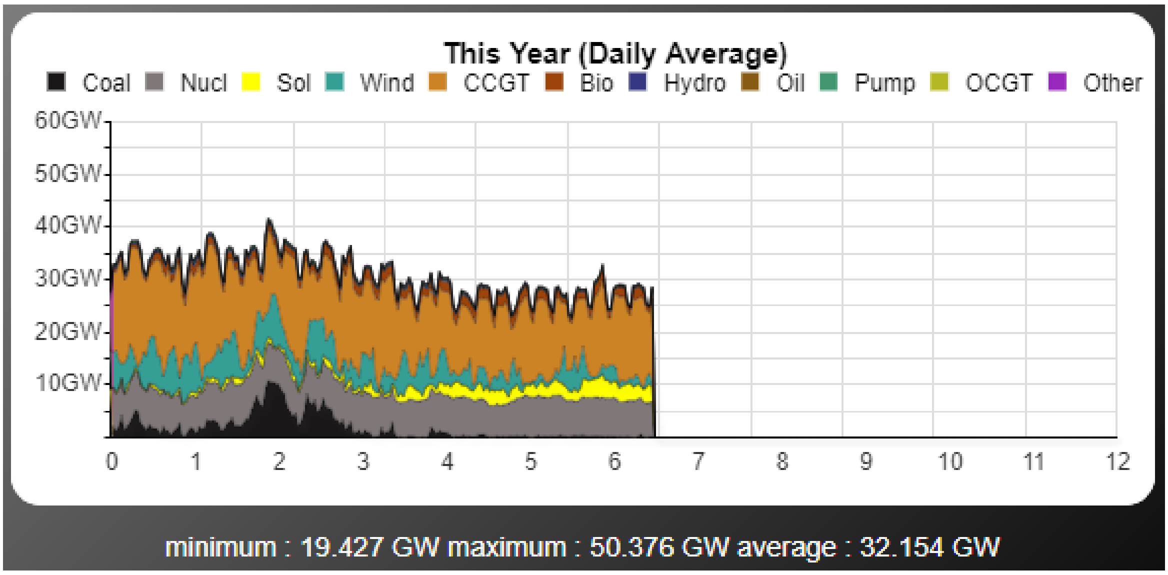


Figure 5: UK 2018 Electrical Power Supply And Demand by Source (Gridwatch, 2018)

As shown, the UK minimum demand for electricity in 2018 was as low as 19.427GW, yet the maximum was more than double this at 50.376GW. Far more power is consumed in the cold winter months to provide domestic and commercial electrical heating and lighting as well as for other industrial processes.

Hypothetically, if the UK were to completely saturate the country with countless numbers of solar panels and wind turbines, there would a definite shortage of power and black-outs would ensue. This is because there is far less sunlight available in the winter months, and there will always be periods where there is no wind at all. In fact, Germany has seen prices of electricity rise along with a rise in carbon dioxide emissions with a large and recent penetration of wind capacity being installed. This is because for every renewable generation source deployed, an equal amount of fossil-fuel generation sources also have to be deployed as back-up source of energy capacity. (Conca, 2017)

Energy Storage

The main challenge with renewables that has still to be solved is energy storage. Energy produced by renewables has to be used as it is generated. When there is excess energy on the grid, grid operators put this excess load back into wind turbines. This is sometimes seen in the UK on days without wind yet the turbines are rotating. This is a complete waste of highly valuable electrical energy. Electrochemical batteries are costly, mining/extraction of their raw materials such as lithium have environmental impacts, and they have relatively low storage and discharge capacities.

Hydrogen production and storage via electrolysis of water is an inefficient process at ~40%. The next step in the process would require vast amounts of energy so that the gas can be compressed up to 500-700 bar for it to have any real practical use for combustion or for transport. Hydrogen molecules are so small that they readily leak from alloy canisters and storage tanks. Leakage rates also increase with higher pressures and poses a real practical challenge with large scale deployment of hydrogen storage. (Barthelemy, 2011)

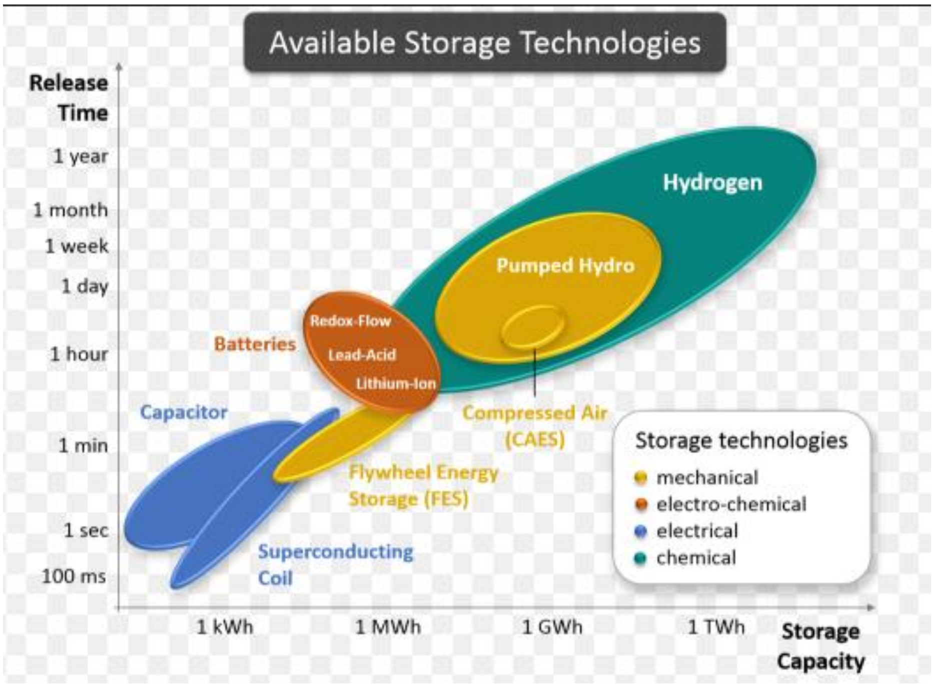


Figure 6: Properties of Different Energy Storage Systems

Another method of energy storage is hydro which the UK has a certain capacity. Hydro is renewable, but unlike solar and wind, electricity generation can be controlled. This is done by allowing the stored potential energy of water being held at a height within a dam to be released through a turbine when needed. This is very important to the national grid operators, as they forecast sudden surges in electrical demand and can easily switch the hydro turbines on within minutes to cope with the rapid increase. Unfortunately, the capacity of hydro power in the UK means that they can only be operational for relatively short periods of time before water-levels run low. This is a geographical issue that engineers have very little control over, as Canada's electricity generation is about 60% compared to the UK's 4%. Until a large-scale storage mechanism is found, we can expect that renewables cannot become our primary source of electricity generation.

CCGT

A breakdown of the UK’s 2016 annual electrical generation by source is shown below in figure 8. As seen, there is a still a significant proportion of electricity produced by natural gas. Natural gas plants use a combined cycle gas turbines (CCGTs) which are far more thermally efficient than any other thermal power plant. Most thermal plants have a thermal efficiency of approximately 30% whereas CCGTs have about 60%. This is because gas is combusted which powers one turbine, but the spent exhaust gas that exits the turbine is still very hot at ~600°C and so can be used to heat water to generate steam that powers a secondary turbine, effectively doubling the work output of one process. This is demonstrated as shown below in figure 7.

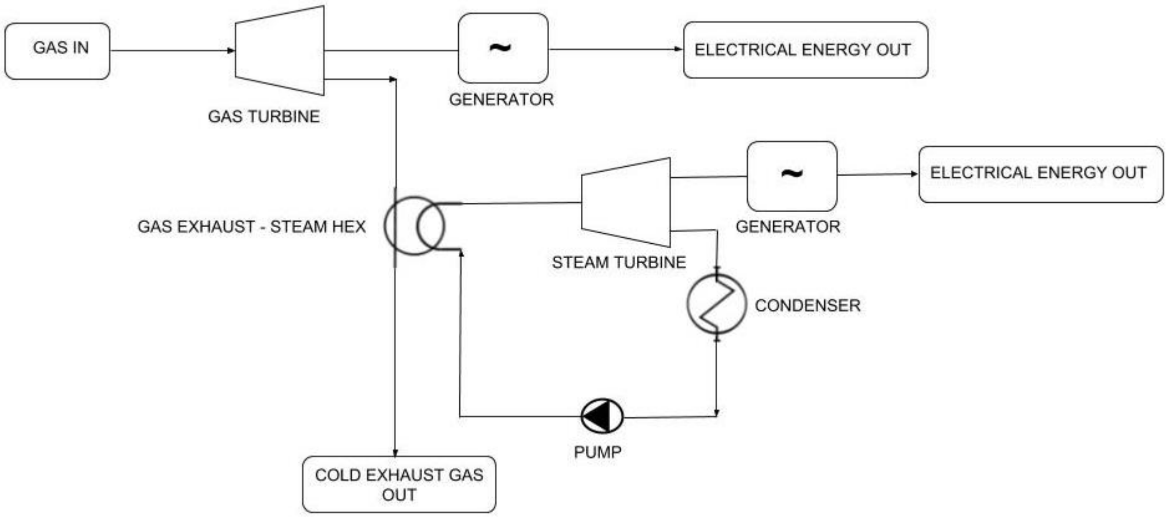


Figure 7: CCGT Power Plant Schematic Diagram

CCGT’s have become the UK’s most dependable source of electricity generation, this is because, like hydro, they are very flexible in terms of their electricity output and can be switched on and off within minutes when required. With a national electricity demand that fluctuates consistently on an hourly basis, CCGT’s currently solve this challenge to provide the varying energy demand at a national scale.

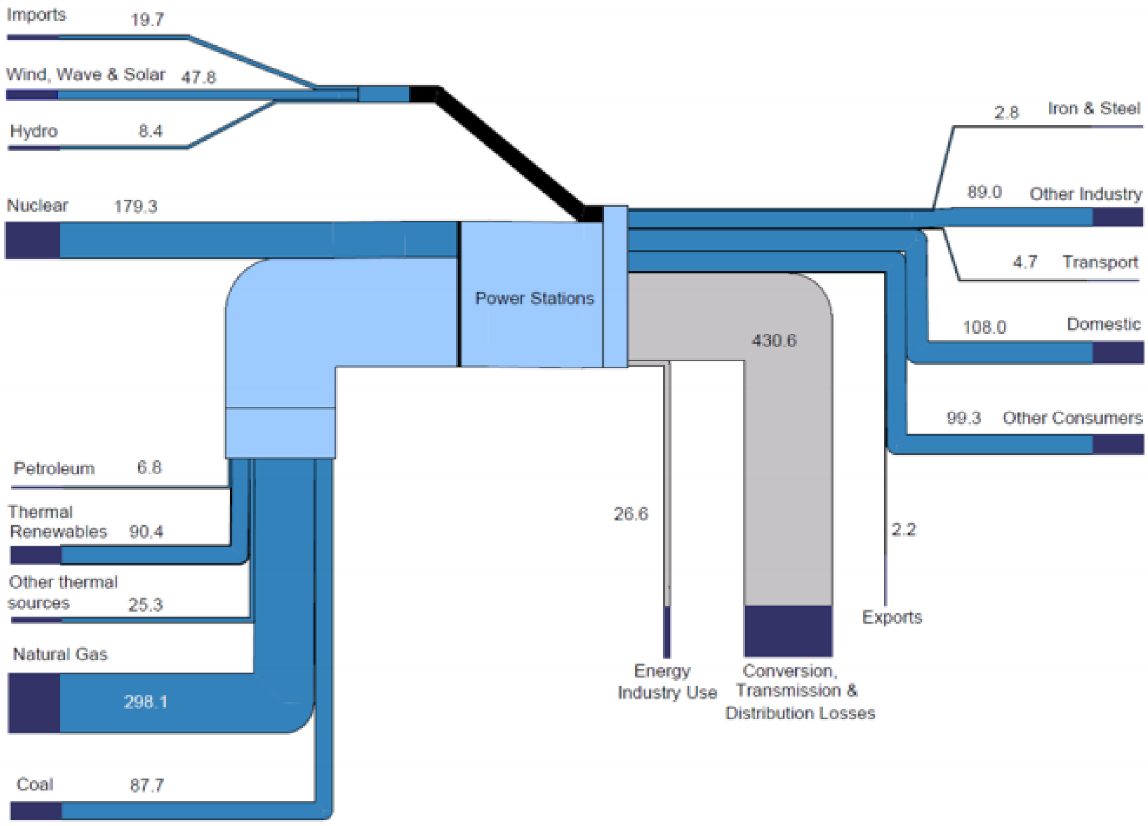


Figure 8: Flowchart of 2016 UK Energy Generation and Consumption (Units in TWh) (Department for Business, 2017)

Nuclear

The most common type of reactor used throughout the world to date is the PWR and the UK's new Hinkley C plant will be 4 PWR's. The current nuclear power stations that operate in the UK are an old fleet of reactors called AGR's (Advanced Gas-cooled Reactors). These were first constructed back in the 1970's, are still operational and rely on heavily outdated technology. For political reasons, the construction of new nuclear plants were banned back in 2007 in Scotland and have been since. That being said, the lifespans of the AGR fleet in the UK have been extended due to lack of other new clean energy generation sources being deployed in the last 10-15 years. (WNA, 2018) These reactors, like any thermal power plants, use heat to generate steam to power a steam turbine for electricity production as shown in figure 9. Unlike CCGT and coal, nuclear power uses nuclear fission instead of chemical combustion to produce heat. This process, unlike combustion, produces zero emissions from its process. That being said, one nuclear fission reaction of a single atom produces 50 million times as much energy as a single molecular combustion reaction, therefore the energy density of nuclear is by far the most superior out of any generation source.

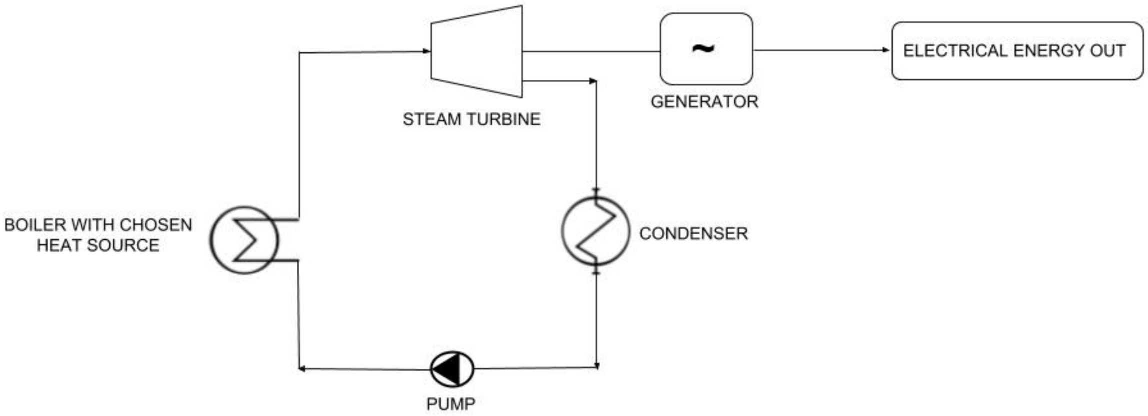


Figure 9: Thermal Power Plant Schematic Diagram

One of major disadvantages of these AGR nuclear power plants is that they have virtually no flexibility in the electrical power output. This can be seen here in figure 10 from the UK's demand by source last year:

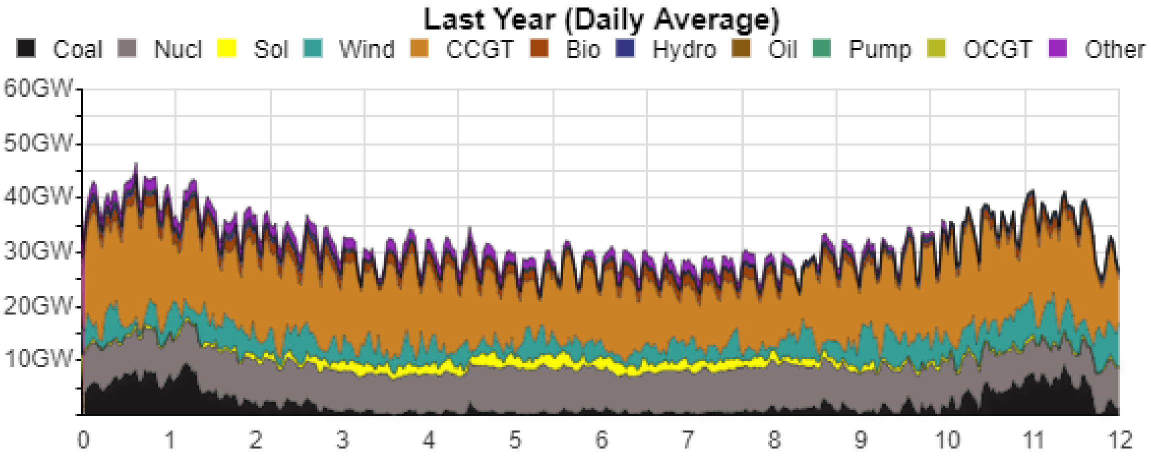


Figure 10: UK 2017 Electrical Power Supply And Demand by Source (Gridwatch, 2018)

In the UK, nuclear is used for supplying the base load only. If they were to constantly vary power output like some PWR's. The PWR's that operate in load-following mode require a lot of complex engineering systems to control the reactivity in the reactor through use of control rods and injection of neutron poison solutions into the water. (Elsheikh, 2013) However, the PWR's that can operate by load following are still slow responding compared to the very fast and effective CCGT's.

With regards to sustainability, which by its dictionary definition means able to be maintained at a certain rate or level. For most cases only renewables fit this category, as with electricity generated from fossil fuel are finite, they will eventually run out if they are consumed at a given rate for long enough. This also begs the question that how much more money should be invested in fossil fuel power technology as they become more and more obsolete.

1.3) Problem Solution

The proposed power generation type would preferably be one that could essentially eliminate all the main disadvantages of each current type of generation source of energy as previously discussed in the problem description. This is demonstrated below in table 1:

Table 1

	Controllable Power Output	Sustainable Long-term	Scalable for Large-Scale Demand	Emission free	Low Capital Cost	No Large Potential Hazard to General Public
Solar	✗	✓	✓	✓	✓	✓
Wind	✗	✓	✓	✓	✓	✓
Coal	✓	✗	✓	✗	✓	✓
Nuclear	✗	✓	✓	✓	✗	✗
CCGT	✓	✗	✓	✗	✓	✓
Hydro	✓	✓	✗	✓	✗	✓
Solution	✓	✓	✓	✓	✓	✓

To show that the proposed system is as flexible and controllable as possible, the electrical power generated will essentially mimic that of a CCGT plant, as CCGT's are used supply power to peak demand periods. This was done by examining data from the UK's national grid. Data on the supply and demand at a nationwide scale is available from Gridwatch (Statistics, 2018) which shows electrical production by each generation source, i.e. wind, coal or nuclear etc. It is essential that the system performs in any situation throughout the year, knowing that the electrical demand varies so greatly throughout the year, as well as throughout the day. Therefore, data was taken from when the UK's national grid experienced its highest and lowest annual demand; 1st of March and the 17th of June of 2018 respectively. It can be seen that the national electrical demand of each from these days varies quite largely, with total demand peaking up to 50GWe in March (winter) compared to 28GWe in June (summer). (Statistics, 2018)To achieve the required high flexibility in electrical power generation the following system was devised and modelled as shown in figure 11.

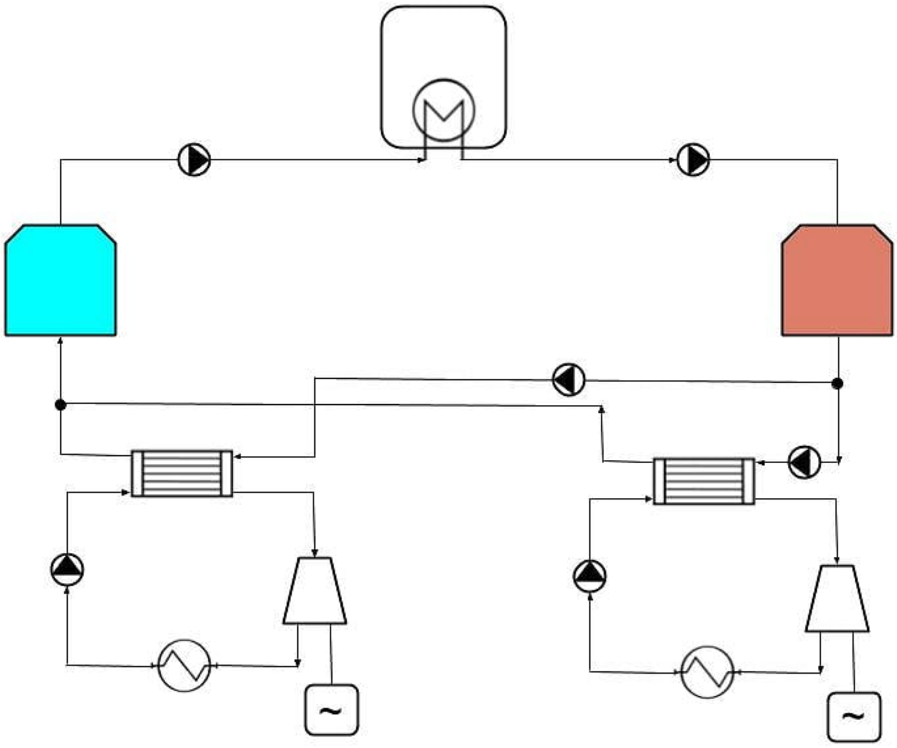


Figure 11: Proposed System Schematic

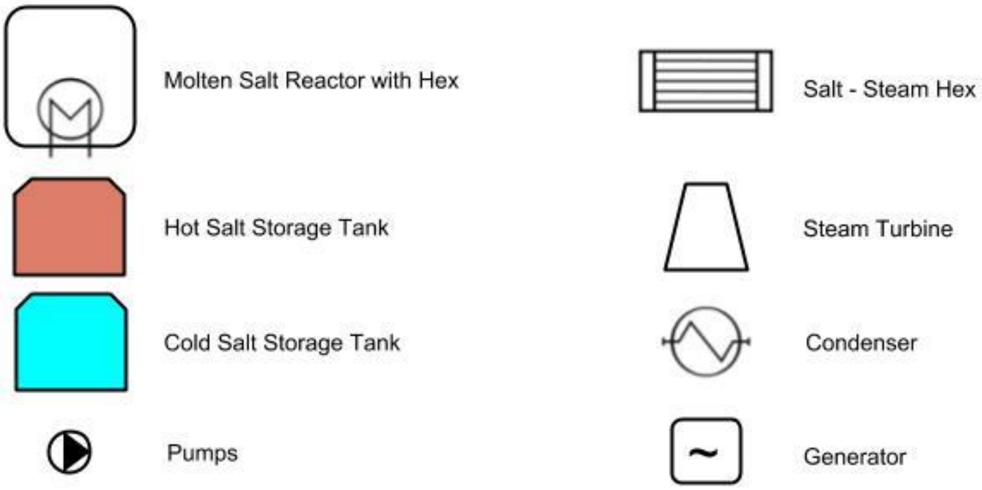


Figure 12: Key for Proposed System Schematic

1.4) Aim of Thesis

The aim of this project is to investigate whether the proposed MSR + TS nuclear generation system can meet the needs for flexible electrical generation in the future UK grid. This was done by designing the system to have identical scaled generation profile to that of the UK's most flexible generation source; CCGTs. The system also would have to whilst also having the following characteristics:

- Sustainable long term with regards to its fuel consumption
- Scalable for a nationwide electrical demand
- Emission free
- Safer than current means of nuclear generation
- Low capital and maintenance costs

If all these criteria are met than it can be said the proposed system is a superior method of generating and supply electricity and that the system should receive more attention and interest by fellow academics as well as from leaders in the energy sector.

1.5) Scope

For this project, the work will be confined to reviewing molten salt reactor technology, thermal storage technology, analysis of the current electricity generation market in the UK and CCGTs power generation. No other country, only the UK's electrical demand profile was used for determining whether the proposed system can provide flexible electrical power for it.

The work will not include fine analysis of material and nuclear science with regards to nuclear reactor neutronics and in-depth chemistry of the working fluids.

The work in this project is purely based on thermal power ratings of the reactor alongside energy and mass balances of working fluid to generate and to store energy.

1.6) Methodology

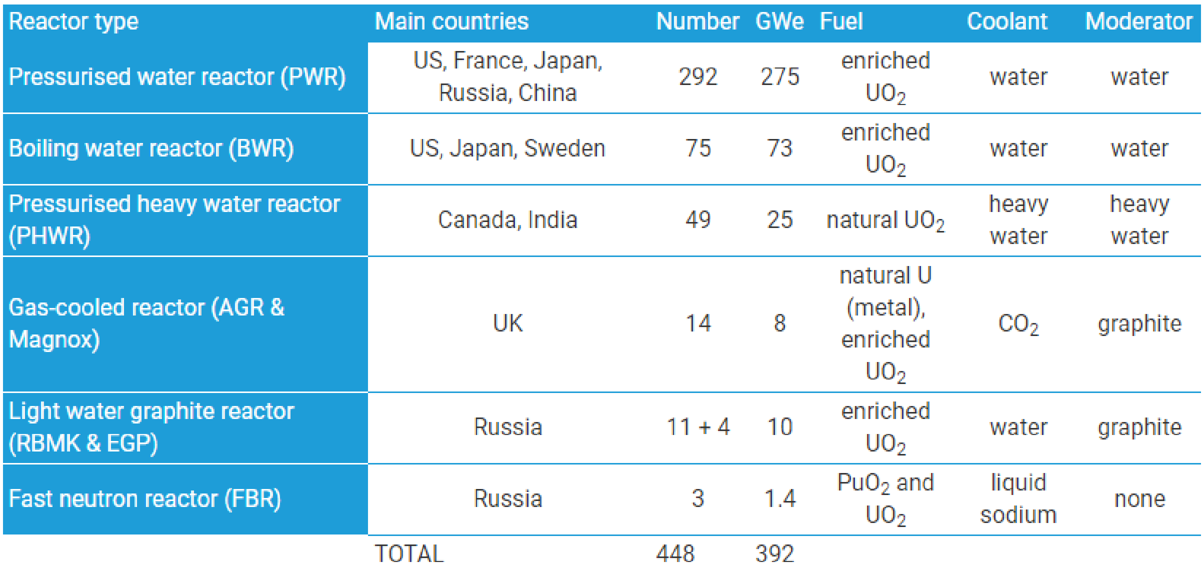
The methods of the work produced in this project was divided into six main sections for the reasoning and intent to flow in a logical path as follows:

- Firstly, a literature review was carried out of MSR technology to determine if it is a superior means of generating electricity relative to conventional nuclear reactors with regards to technical and functional operation, safety issues, nuclear waste, and cost.
- A literature review of TS to determine the advantages and disadvantages of using molten salt as a means of thermal energy storage with regards to operation, safety issues, and cost.
- Analysis of the UK's electrical supply and demand throughout a seasonal basis to understand the full requirements of the proposed system.
- To design a working model of the combined MSR and TS technology that is both technically and practically feasible.
- To collect results and discuss if the proposed system is worthwhile concept to continue academic and industrial interest in this field.
- Conclude with the proposed system's advantages and disadvantages, and its importance in the futures energy market with regards to sustainability.

(2) LITERATURE REVIEW – MSR

2.1) Introduction

Operating an MSR system over the most standard PWR system is far different even though both are a type nuclear reactor. This is mainly due to the MSRs fuel being in a liquid state rather than in a solid (such as the PWR). The design principles that every solid fuel reactor use to this day are completely changed due to the physical state of the fuel. The PWR design was chosen to compare with the MSR as it is the most common type of reactor in operation to date as shown in figure 13. The other five types of Gen IV were not included in this report as they all use fuel in their solid states.



Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia, China	292	275	enriched UO_2	water	water
Boiling water reactor (BWR)	US, Japan, Sweden	75	73	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	25	natural UO_2	heavy water	heavy water
Gas-cooled reactor (AGR & Magnox)	UK	14	8	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (RBMK & EGP)	Russia	11 + 4	10	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	3	1.4	PuO_2 and UO_2	liquid sodium	none
	TOTAL	448	392			

Figure 13: Global Data for Currently Operation Reactors (WNA, 2018)

Schematic diagrams illustrating the PWR and MSR systems are shown below in figure 14 and 15 to distinguish some key features:

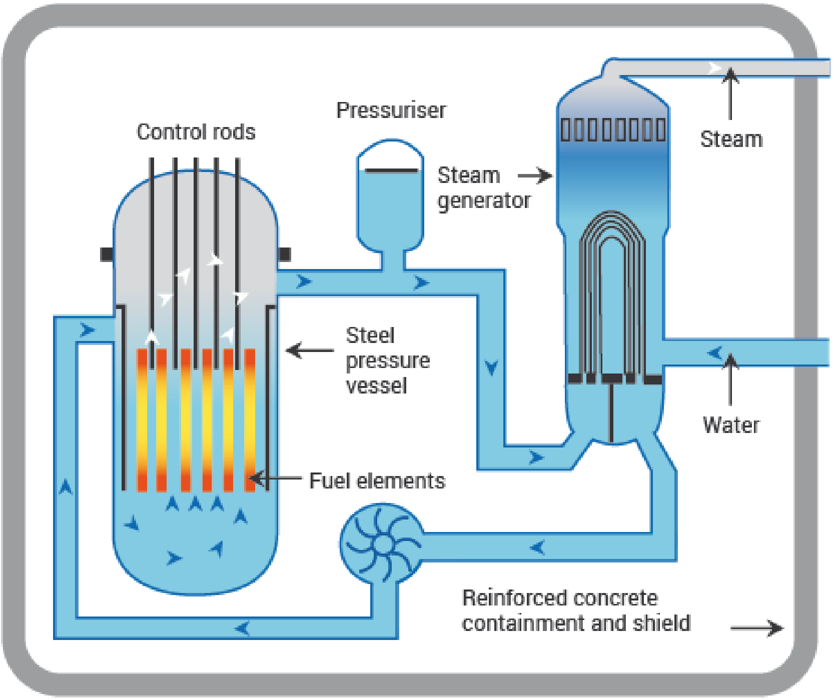


Figure 14: PWR Schematic Diagram (WNA, 2018)

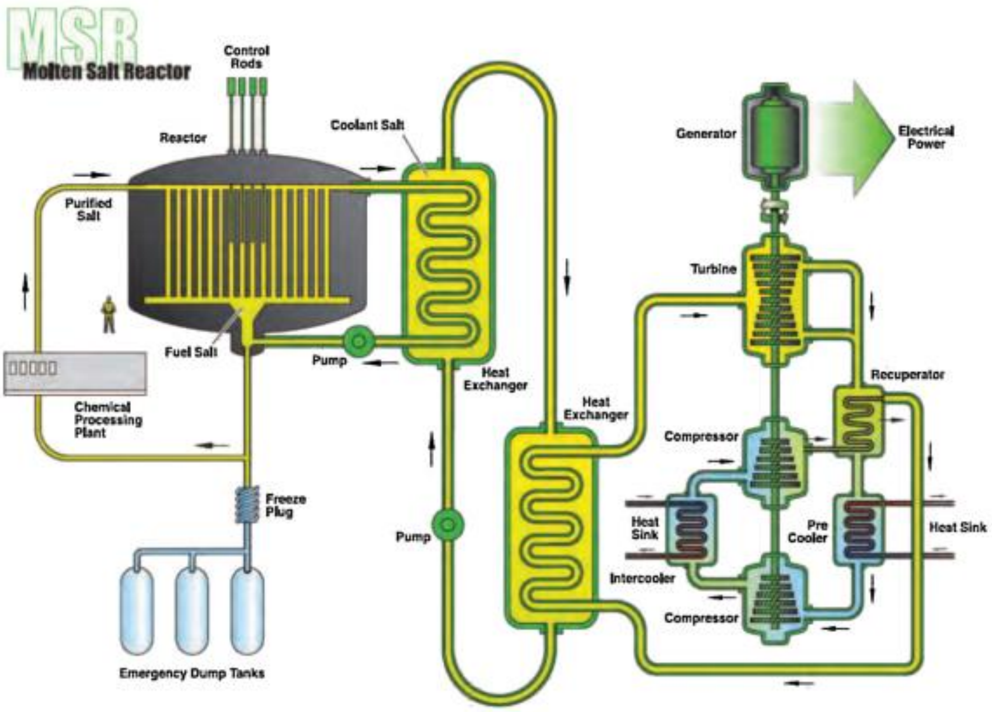


Figure 15: MSR Schematic Diagram (Wiki, 2002)

2.2) Common Safety and Technical Advantages with MSRs over PWRs

Pressure

With PWR systems, water is used both as a primary coolant and a moderator for the reactor. Moderators are required in thermal reactor systems to ‘slow down’ neutrons to sufficient energy levels to induce a fission reaction with a fissile uranium atom. Standard light water boils at 100°C, yet PWR’s operate at 315°C. This means that the reactor has to operate at high pressure up to 155 bar. If the reactor vessel were to experience damage causing a leakage, the water inside has a large driving force to exit the reactor into the surrounding atmospheric pressure environment. If this were to happen, as soon as the 315°C water comes into contact with the ambient air, it would instantly vaporise/flash into steam. (Elsheikh, 2013) When water flashes to steam, its volume increases 1000x, creating a risk for an explosion. For this reason PWR systems require large robust reinforced concrete containment shields, as well as thick heavy duty piping.

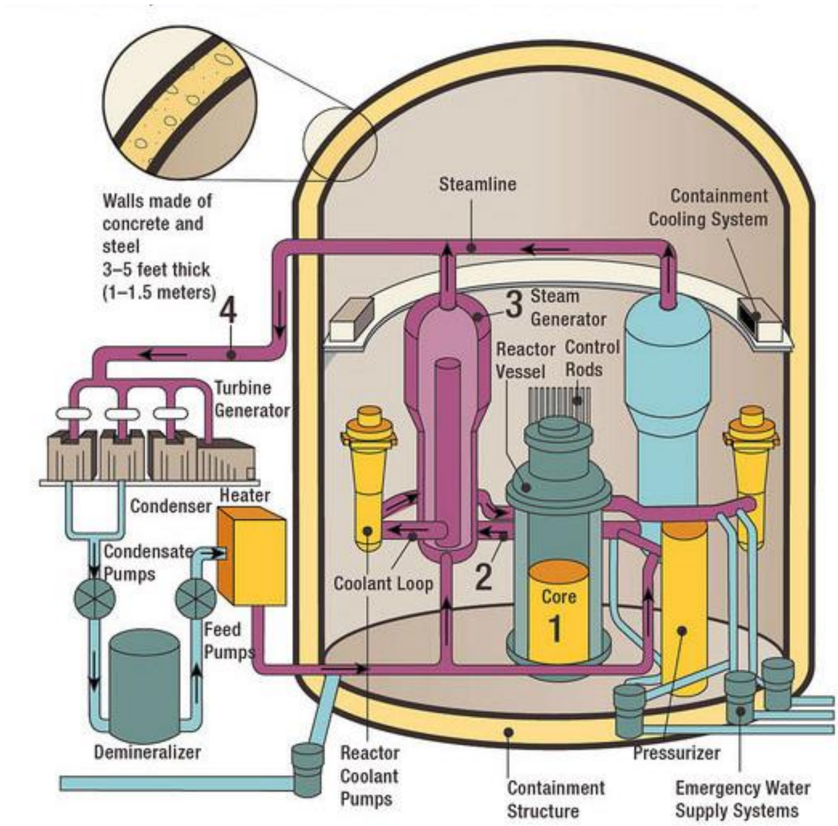


Figure 16: PWR Containment Structure and Components Schematic Diagram (NRC, 2015)

If pressure is lost in the PWR, steam forms in the core, thereby reducing the heat withdrawal from the core. This elevates the core temperature, and the zirconium fuel cladding can react with the steam at temperature above 800°C forming hydrogen and oxygen, thereby creating an explosion hazard. This scenario was witnessed at Fukushima.

In a MSR system, the reactor nominal operating temperature is ~750°C, however, salts in their molten liquid state emit virtually no vapour pressure. (Elsheikh, 2013) This means that the system can operate at near atmospheric pressure. If the reactor vessel walls were to rupture, there would be little to no driving force to expel the liquid salt. Instead, the salt would trickle out, in some cases if the rupture was small enough, the salt would come in contact with the ambient air and freeze back into its solid state, forming a plug, effectively becoming a self-sealing system.

Chemical Stability

Another feature of using salts in their molten state is that they remain chemically inert. Unlike liquid sodium metal fast breeder reactors, there is no risk associated with fire or explosion if the molten salt were to come into contact with air or water/moisture. Sodium in its solid or liquid state is highly reactive therefore intensive safety measures have to be installed in construction, maintenance and operation so that it never comes into contact with air/water.

Fission and decay products; caesium and iodine are specific health hazards as they are highly radioactive that can be taken into the human biological mechanisms and pathways. This is due to the chemical properties; caesium is recognised by the body as sodium or potassium, which are used in biochemical pathways within human cells, as is iodine which is processed in the thyroid gland. However, as they are radioactive with relatively short half-lives, they emit beta and alpha particles at a relatively fast rate. These alpha and beta particles have strong ionising properties which can damage human DNA and can lead to cancer. As they remain trapped inside the fuel pellets at high pressure over 100bar, if the fuel pellets and cladding are damaged due to meltdown, the gases have a large driving force to be expelled into the surrounding environment. (Rosenthal, et al., 1972) This was first witnessed at Chernobyl when the reactor experienced full meltdown and radioactive gases were released into the atmosphere where weather patterns carried them as far as Sweden and parts of Scotland. This is highly problematic, as the gases can travel very far and can end up in the food chain. They can be absorbed or can fall onto plants which are then eaten by agricultural animals which are then ingested by humans.

With molten salt reactors, this problem is completely avoided as gaseous and highly radioactive iodine and caesium form fluorides and iodides in the salt. (Rosenthal, et al., 1972) Essentially, the iodine and caesium dissolve and remain in the molten salt, so if the reactor vessel were to be damaged/ruptured, they would simply remain in the salt and would not be expelled into the air. (Moltex, 2018) Additionally, fuel catch basins can be installed directly below the reactor to 'catch' any leaked molten fuel salt if the vessel wall were to rupture.

Thermophysical Stability

Most PWR's operate at approximately 315°C and 155 bar, this means that if there is a coolant failure and temperature increases, the water will boil at 344°C as shown in figure 17. Once this happens all control over the reactor is lost and meltdown of the reactor will occur. Depending on the mole ratio of ions within the salt, typical molten fuel salt has a boiling point of 1400°C or more, much greater than the operating temperature of 700°C. A MSR has a far greater operating temperature range of 700°C rather than a PWR's mere 29°C. It can be said that the pressure of an MSR system cannot increase. (Elsheikh, 2013)

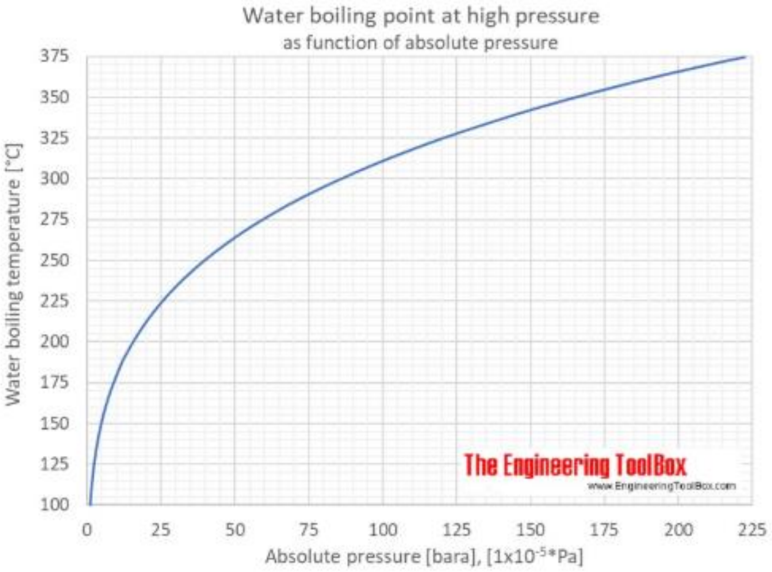


Figure 17: Boiling Point of Water with Increasing Pressure

Large Fast-acting Negative Temperature Coefficient

The fuel salt inside the core of a molten salt reacts promptly to temperature. If the temperature of the reactor increases, the liquid salt expands. This does two things; the salt expands considerably, thereby decreasing the density making the probability of fission less likely to occur as the atoms are spread further apart. Expanding the fuel salt also pushes fuel outside the high temperature graphite moderated core. (Elsheikh, 2013) As the fuel leaves the graphite moderator, neutrons are not ‘slowed down’ to sufficient energy and fission ceases. Consequently, the MSR is said to be self-controlling, as reactivity decreases with increasing temperature within minutes without operator intervention as shown below in figure 18, and vice versa. Temperature of the reactor is controlled by adjusting flow rates of both working fluids in the primary heat exchanger. (Merle, et al., 2015)

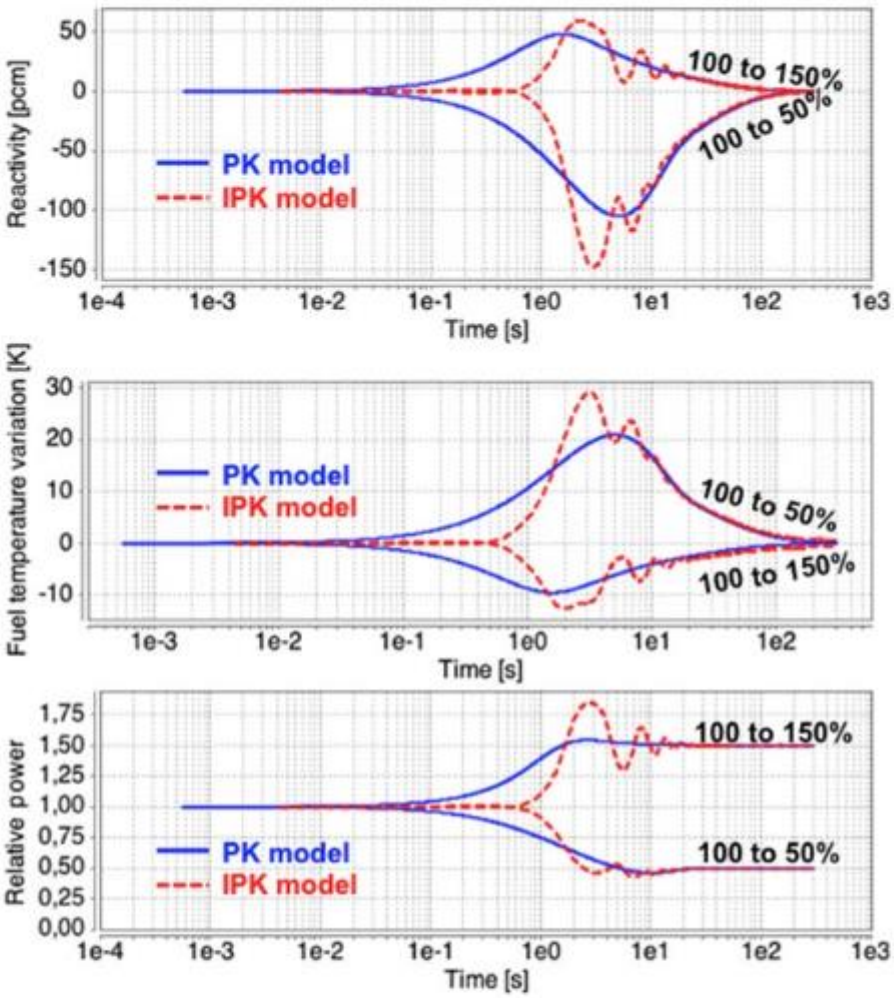


Figure 18: Reactivity, Fuel Temperature Variance of Simulated MSR Operation (Merle, et al., 2015)

Designed Criticality

The reactor can be designed so that the fuel salt just reaches criticality only when it is in the presence of graphite in the core. If a primary heat exchanger experiences a failure/rupture, the primary and secondary coolant salt mix, thus diluting the fuel salt and the entire mixture becomes sub-critical. This eliminates the possibility of any criticality accident if the fuel salt is leaked into the secondary coolant. (Elsheikh, 2013)

Less Control Required

The fuel salt composition can be altered at any time by adding or removing fissile or fertile fuel through online chemical processing. Through also having the fuel in a liquid form can allow for the geometry of the reactor to change. This can be done with installing graphite moderator rods instead of neutron absorbing control rods. This is beneficial compared to PWRs where excess reactivity has to be controlled when fresh fuel rods are inserted into the reactor during refuelling. (Transatomic, 2016)

Removal of Gaseous Fission Products

Noble fission products such as krypton and xenon form as gases at MSR operating pressures. These krypton and xenon are strong neutron poisons and display real performance problems is current PWR reactors. In an MSR system, the gases form into bubbles which can be removed continuously with inert gas sparging process which was successfully managed in the MSRE. In turn, removal of gaseous neutron poisons increases reactor performance and fuel burnup as less neutrons are lost and instead induce fission. (Rosenthal, et al., 1972)

Freeze Plug

One of the largest safety benefits of using an MSR system unlike PWRs is taking advantage of the physical state of the fuel. In a PWR the fuel is solid and requires very controlled mechanical processes of moving the fuel in and out the reactor. Fuel can be only moved when the reactor is shut down and depressurised and not in the event of an emergency. If PWR reactivity control is lost, operators are very limited in how they can regain control. After an emergency situation, such as a loss of power to the reactor plant site, these overheating accident scenarios can develop within minutes. (Elsheikh, 2013) A PWR filled with solid fuel pellets that are poor heat conductors can require cooling to the reactor for years before decay heat drops to a negligible level. This mismatched timing (minutes to overheat versus years to cool off) makes nuclear safety for not only PWRs, but every solid fuelled reactor enormously challenging and leaves these reactors particularly vulnerable to extremely rare disasters that were not incorporated into the reactor’s safety profile, known as “beyond design basis” accidents. (Transatomic, 2016)

If a system failure were to occur in an MSR and temperature were to escalate far above designed operating temperature, the ‘freeze plug’ (seen in figure 15) located at the bottom of the reactor melts, allowing the fuel salt to drain from the moderated core into a drain tank without the use of pumps and relying on gravity instead. The drain tank has no moderator in it and can also have neutron poisons to quickly make the fuel salt sub-critical, stopping the reaction. Another feature of the drain tanks is that it is designed to maximise passive heat withdrawal. Reactors are designed to minimise heat loss to their surrounding environment to increase thermal efficiency, with the drain tank it is designed to do the opposite. (Elsheikh, 2013)This is how Fukushima could have been avoided, as the tsunami took out the diesel generators which were to power the cooling pumps. Without coolant being pumped to the reactor, decay heat still being generated in the reactor accumulated and the reactor experienced partial melt-down and a hydrogen explosion. In the same situation, without an external power supply, the MSR would have drained the fuel to the drain tank where it is passively cooled by natural air convection, eliminating the need for back up diesel generators.

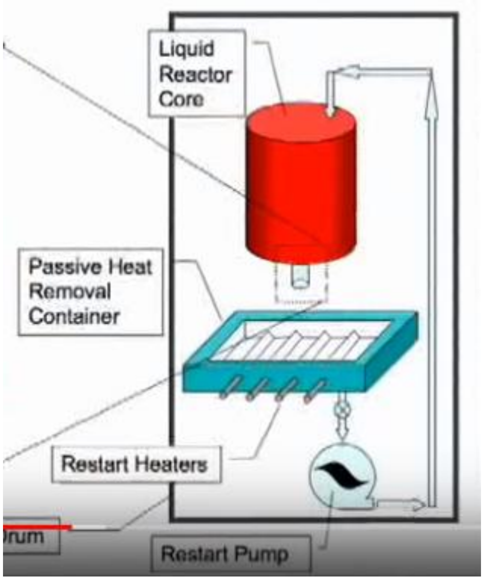


Figure 19: Example of MSR Drain System with Fuel Salt Recovery (Bonometti, 2008)

Another highly beneficial aspect of this is that the reactor can be recovered. The salt in the drain tanks can either be disposed or reheated and fed back into the reactor after an overheating event such as a heat exchanger failure.

Higher Burn-up (fuel can stay longer in reactor)

In standard solid-fuelled reactors, uranium fuel pellets are arranged vertically and sealed in fuel pins made from zirconium alloy. Over time, gaseous fission products build up as the reaction continues, increasing pressure inside the fuel pin up to 100 bar. Major gaseous fission products such as xenon-135 and krypton-85 are very effective neutron poisons. Fuel pins can remain in most conventional solid-fuel reactor for up to 4 years until the xenon and krypton build-up is too high and begins negatively effecting reactor performance. In the MSR this is completely avoided again as the gases can be continually removed via gas sparging with helium. (Haubenreich & Engel, 1969) This means that the fuel can be cycled inside the reactor continually and is not limited to a 4 year duration, thus vastly increasing fuel burnup per unit mass of fuel initially added to the reactor. (WNR, 2018). Although gas sparging was carried out throughout the MSRE, the process was not perfected and requires further investigation and research.

Superior Heat Transfer

Salt in its liquid molten state has very good volumetric heat capacities. Water remains superior, however, the other three proposed coolants for the Gen IV reactors have significantly less heat capacities than the salt. This is an added safety/technical feature as more heat can be transferred throughout the system per unit volume of coolant pumped to the reactor, therefore it can be cooled down and controlled quicker and also allows the reactor to be more compact in size.

Table 2

Coolant	Heat Capacity (kJ/kg K)	Density (kg/m^3)	Volumetric Heat Capacity (kJ/ m^3 K)
Water	4.18	1000	4180
Salt	1.68	1600	2688
Sodium	1.23	968	1191
Lead	0.13	11340	1451
Helium	5.19	0.16	0.83

In standard solid fuelled reactors, the fuel pellets producing the heat from fission have poor thermal conductivities to the zirconium fuel pins and the fuel pins to the primary coolant. This heat transfer rates further decreases over time as gaseous fission products build up inside the fuel cladding.

Reduced Refuelling Complexity due to Homogeneous Fuel Mixture

In standard solid-fuelled fast and thermal reactors, refueling is a complex procedure. Each fuel assemblies spends approximately 4 years inside the reactor before it is removed completely. Throughout the 4 year lifespan inside the reactor, the fission reactions consumes its fuel whilst generating more fission products. These fuel pins, therefore, change in composition over time, becoming less effective at generating neutrons and sustaining fission reactions as the fuel is consumed. These fuel pins are mechanically shuffled towards the outside of the core whilst new fresh fuel assemblies are inserted in the center of the core. (Wakker, et al., 2003) This is can be completely avoided in the MSR due to the fuel being liquid. The fuel in the form of a liquid remains homogeneous; fresh uranium can be simply added to the salt and will disperse and equally distribute itself through diffusion. (WNA, 2018) (Rosenthal, et al., 1972)

Thermal Breeding Opportunity with Thorium

Conventional thermal reactors use enriched uranium, which has slightly higher content of fissile uranium-235 than found in natural uranium ore when it is originally mined. This is a highly energy-intensive and costly process as separation of element of different isotopes is difficult. Thorium is 4x abundant than natural uranium and is found in every continent. Thorium-232 is not fissile, but it can be placed around thermal reactor cores in regions called blankets. Excess neutrons from the core penetrate into the blanket region and is captured by the thorium atoms. Thorium-233 is an unstable isotope and beta decays into Protactinium -233 over a period of approximately 30 minutes. The Protactinium further decays into uranium-233, which is fissile and can be used directly as nuclear fuel. This is seen as advantageous as breeding fuel from thorium does not require expensive isotope separation that is used in uranium enrichment. It is it far easier to separate fissile U-233 from thorium/protactinium, this is because they are different elements so only chemical separation is required. (Haubenreich & Engel, 1969)

2.3) Advantages with Fast Spectrum MSR over thermal MSR

Fissile, Fertile and Fissionable

‘Natural’ uranium is mined from the ground and contains 0.7% U-235 and 99.3% U-238. U-235 is the readily found fissile isotope of uranium. Fissile cross sections of U-235 increase vastly as the energies of neutrons decrease down to ‘thermal’ energies (~0.025eV) as seen in figure 21, meaning that the probability of a fission event is much more likely to occur. Most (thermal) operational reactors use enriched natural uranium through processing to increase U-235 content to 3-5%. Heavy water (D_20) reactors do not need to enrich fuel as heavy water used as the moderator is highly efficient.

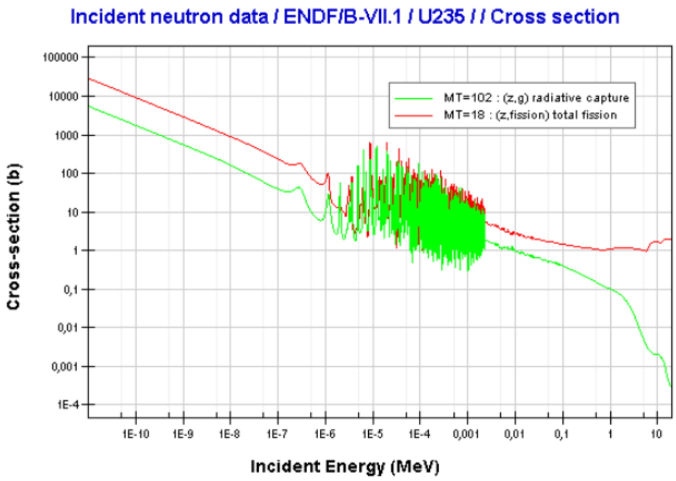
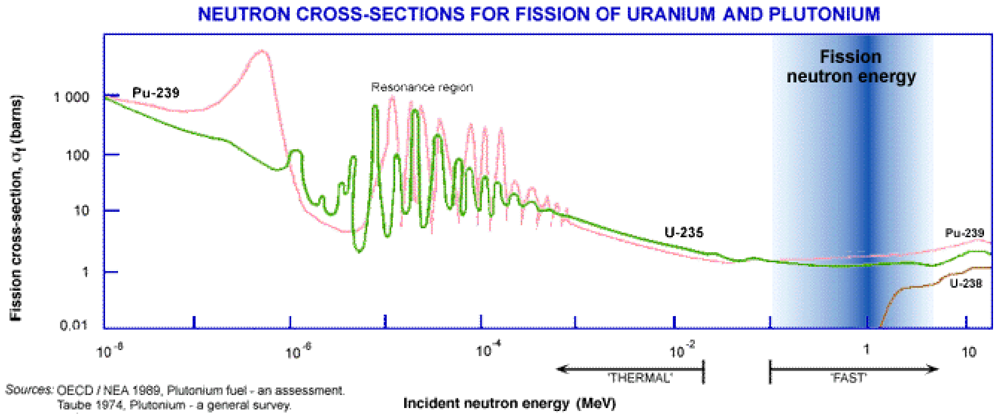


Figure 20: Incident Neutron Data for U-235 (nuclear-power.net, 2018)

When a fission reaction of a U-235 atom occurs, the average number of neutrons released is 2.45. For a nuclear fission reaction to be sustained in a reactor, at least 1 neutron is required to be released to strike another available U-235 atom in order to sustain the reaction at criticality. In reactors, neutrons are lost/absorbed by different materials in the reactor, such as some physical components of the reactor, some into the fission products that build up over time as the reaction proceeds and others absorbed into the U-238.

U-238 is not fissile, as seen from comparing cross sections of both isotopes in figure 22 and 24, its fission cross section is very small so that the probability of fission event at thermal energies is virtually zero. U-238 is a fertile and fissionable material. If a U-238 absorbs a neutron, it becomes U-239, then beta decays (releases an electron from a neutron thereby increasing the atomic number transmutating into another element) into Neptunium. Neptunium beta decays again transmutating into Plutonium, which is fissile as shown in figure 22.



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28} m2, 1 MeV = 1.6 x 10^{-13} J

Figure 21: Neutron Cross-sections for Fission of U-235,238 and Pu-239 (WNA, 2018)

Breeding

Fast breeder reactors are designed to have a region of U-238 surrounding the core called the breeding blanket. Excess neutrons from the core are absorbed by the blanket, most of these neutrons have lost a majority of their original energy and so are completely absorbed by the U-238. The breeding ratio is defined as the ratio of new fissile nuclei to fissioned nuclei; in a normal reactor is around 0.6, that in a fast reactor may exceed 1.0.

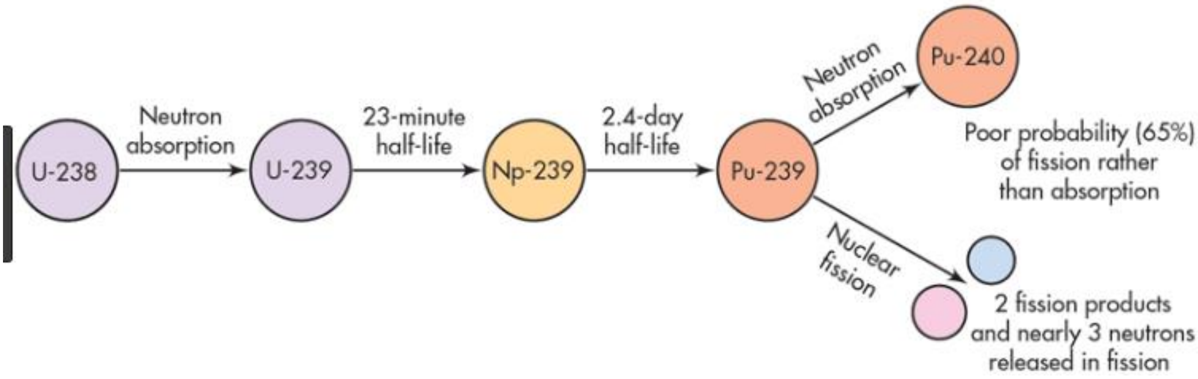


Figure 22: U-238 Transmutation to Pu-239 (Sorensen, 2016)

U-238 is also fissionable, demonstrated in in figure 24, if the neutron energy level is high enough, it increases the possibility of fissioning the atom, however, only a small portion of U-238 is fissioned this way inside the core.

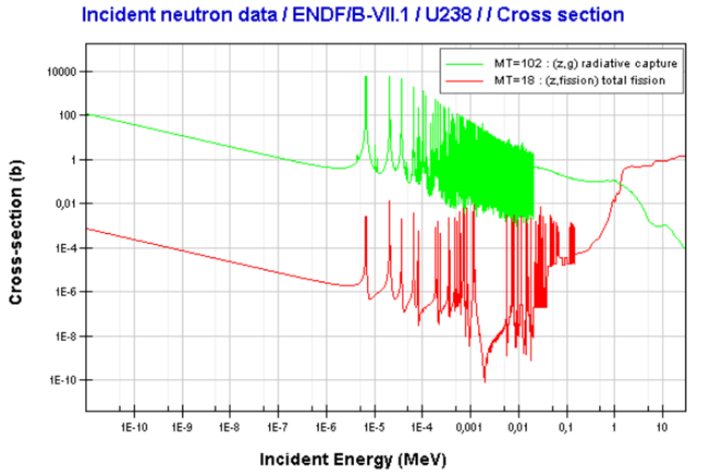


Figure 23: Incident Neutron Data for U-238 (nuclear-power.net, 2018)

Higher Power Density

Since fast reactors use no moderator in the core, it also leads to smaller, more compact designs with higher power densities. The downside to fast reactor is that the fuel initially charged into the reactor has to be enriched further than thermal reactor fuel, 3-5% to 10-15%.

This was thought to raise concerns with nuclear proliferation due to the possibilities of nuclear fuel processing plants, however weapons grade has to be significantly further enriched; up to 99% fissile material.

Higher Fuel Utilisation

Fast reactor are regaining interest as they have far greater capabilities of utilising more uranium. This is because thermal reactors burn only 3-4% U-235, the remaining fertile U-238 goes unused as shown in figure 25:

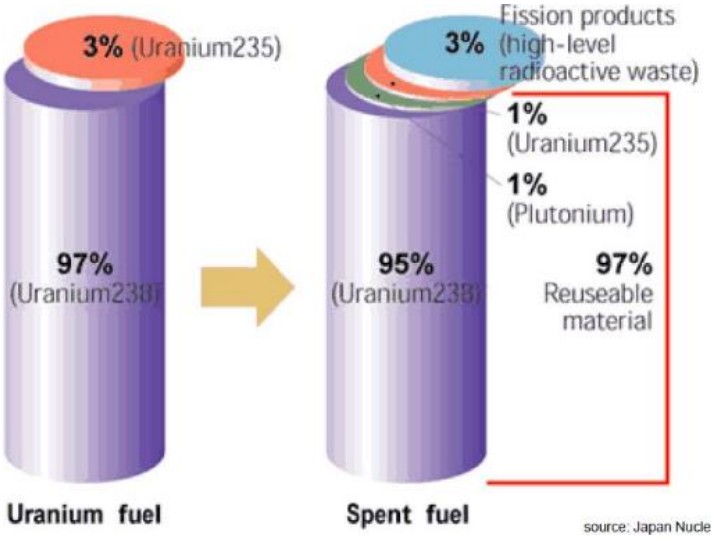


Figure 24: Comparison of Composition of Fresh fuel & Spent Fuel

Fast spectrum reactors use no moderator and rely on only high energy neutrons to induce U-238 fission in this way, whilst also converting U-238 into Pu-239. When a reactor converts a fertile material such as U-238 into fissile Pu-239 and has a breeding ratio of 1.0 or more, it is called breeding, hence the name, fast breeder/fast reactor. Fast breeder reactors received a lot of interest in the 1970's when natural uranium resources were thought to be scarce and so the breeding of more abundant isotope U-238 was thought to be necessary.

Graphite and Xenon Problems Avoided

Another benefit of implementing fast spectrum MSR's is that potential xenon and graphite problems are avoided. Xenon forms as a gaseous fission product and is a very potent neutron poison, but this is only with neutrons with thermal energies. (Moltex, 2018) The MSRE at Oakridge, xenon was expected to be rapidly removed through helium sparging, however, the reactor still experienced power transients that could not be fully explained due to lack of understanding of the gas behaviour. (Haubenreich & Engel, 1969)

To optimise chemical stability of the molten salts, the reactor can readily keep them in a strongly reducing state through the use sacrificial anodes and cathodes. (Moltex, 2018) Graphite has been seen to slowly react with molten salt at levels of high irritation/high power densities, consequently putting the salts into a more oxidative state. Oxidised salts should be avoided as much as possible to reduce metallic corrosion of internal reactor components. Through use of fast spectrum MSRs both potential problems with graphite and xenon are inherently eliminated.

2.4) Review of Moltex Energy's Technical Paper

Waste Burner Concept

Moltex Energy is a UK based start-up company currently developing a fast-spectrum MSR called the SSR (Stable Salt Reactor). It does have breeding capabilities but has a breeding ratio less than 1.0. A breeding blanket is not incorporate in their preliminary/conceptual design, instead, the design optimises neutron reflection back into the core, which vastly increases neutron flux which in turn increases fission rates of long-lived actinides (Pu-239, Pu-240 etc).

The SSR with its fast neutron spectrum operation and high neutron flux inside the core allows it to have the ability to burn highly impure plutonium; the fuel can contain as much plutonium as it does lanthanides (fission products). This allows Moltex's SSR to burn existing stockpiles of nuclear fuel with minimal reprocessing of the stockpiles; reducing costs. (Moltex, 2018)

Reduced Reactor Complexity

The SSR design is different from other current conceptual MSR designs as the company's main focus is attempting to achieve approval of the UK Nuclear Regulators as soon as possible for quickest deployment of the reactors.

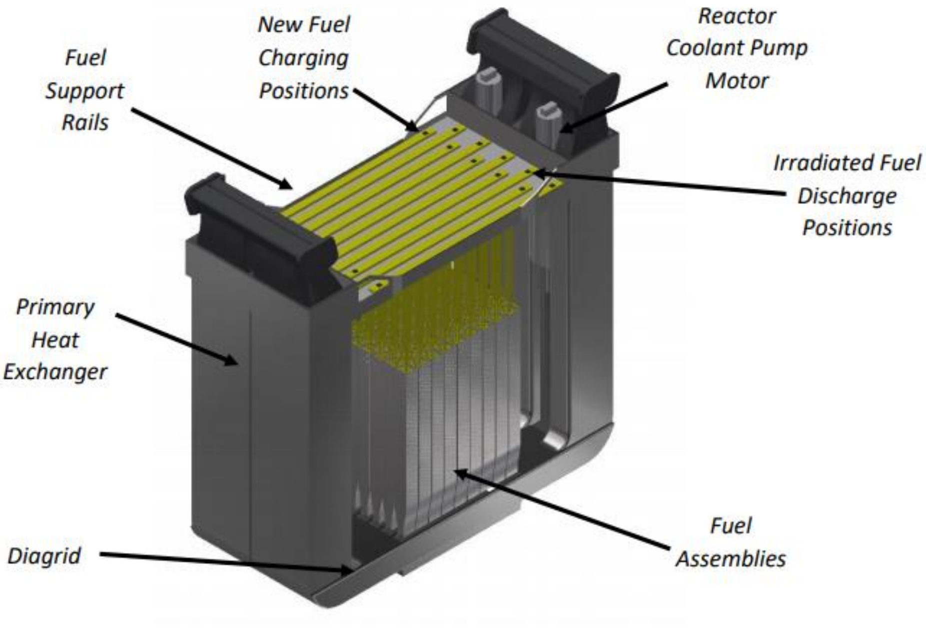


Figure 25: Moltex Energy's Layout of SSR Module (Moltex, 2018)

The design shown in figure 26, has the fuel salt being looped around several pieces of equipment (chemical processing and heat exchangers). This will create further challenges, mainly maintenance issues, as the fuel salt is highly radioactive, all maintenance and repairs to chemical processing equipment and heat exchangers must be done robotically/mechanically to avoid human contact as much as possible. Having radioactive fuel salt circulate and contact several pieces of process and system equipment will also increase the amount of intermediate level waste when it comes times to decommissioning the plant. This will inevitably drive up capital, maintenance and decommissioning costs as the hazards and associated risks are increased. Having the fuel salt flow circulating several pieces of equipment also requires sufficient material research for regulators to confirm salt corrosion and irradiation damage rates are to a satisfactory level. I.e. the more pieces of equipment the fuel salt circulates and comes into contact with, the more expensive it will be to carry out adequate research on the effects, also increasing the time period for regulatory approval. (Moltex, 2018)

The SSR avoids this by instead of having the fuel salt circulating the system, the fuel salt is located in individual fuel pins called fuel assemblies, similar to how standard solid fuel pellets are placed inside fuel cladded pins in all current reactor designs. The heat generated in the individual fuel pins is transferred to a primary coolant, which surrounds the pins in a bath-tank like configuration as shown in figure 26. The fuel salt inside the fuel assemblies circulates naturally through convection which reduces the risk of hot-spot within the reactor. Moltex uses steels currently tried and tested in the nuclear reactors for fuel pin assemblies thus requires less time for regulatory approval as neutronic data with these steels already exists. Each individual fuel has a venting system to release gaseous fission products within the fuel salt. Bubbles form and rise within the salt and are gradually vented through the diving bell gas vent as shown in figure 27. This prevents pressure build up inside the fuel pins, which happens in conventional solid fuelled reactors when the fuel pins are completely sealed.

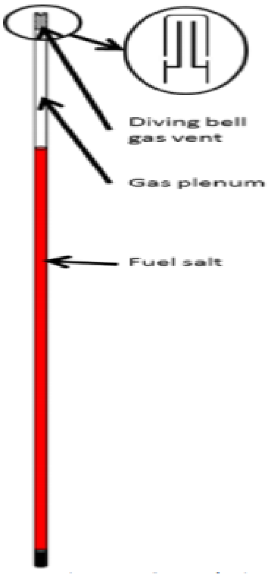


Figure 26: Moltex Energy's Individual Fuel Pin Design (Moltex, 2018)

Radiation Protection

Another advantage of this design is that the primary coolant, which is also a molten salt, has a different elemental composition than the fuel salt inside the fuel assemblies. The primary coolant is proposed to have hafnium dissolved in the salt, which is a strong neutron absorber. Having a strong neutron absorber in the primary coolant makes it an effective neutron screen, protecting other components of the reactor such as heat exchangers and primary coolant pumps from irradiation damage, maintaining structural integrity thereby increasing the operational lifespan of the system. Another benefit of having neutron absorbers within the coolant is that if a fuel pin were to rupture and leak, is would quickly diffuse into the coolant, diluting the fuel salt, thus making it sub-critical. (Moltex, 2018)

Passive Heat Removal

The SSR does not use any control rods but relies on the strong negative temperature coefficient of the fuel salt. The reactor is either operational or shutdown; if operators want to shut down the reactor they do so by inserting neutron absorbing blades. The reactor does not include a drain tank, if the power is lost to the site and primary coolant pumps cannot be used, the outside of tank is surrounded by a jacket of air ducts that use natural convection of outside air as a hint sink which effectively controls decay heat. Including inherent passive air cooling allows the design to have a far greater power density. Simulations carried out by Moltex show that the maximum temperature reached in the reactor is 860°C (figure 28), however, as the temperatures increase to a large enough extent, the surrounding ambient air ~20°C becomes a more effective heat sink as the temperature difference between the two mediums increases. In the unlikely event of this happening, it is a comparable experience to a meltdown in a PWR but the radiological consequence is much lower and the SSR is recoverable after the event.

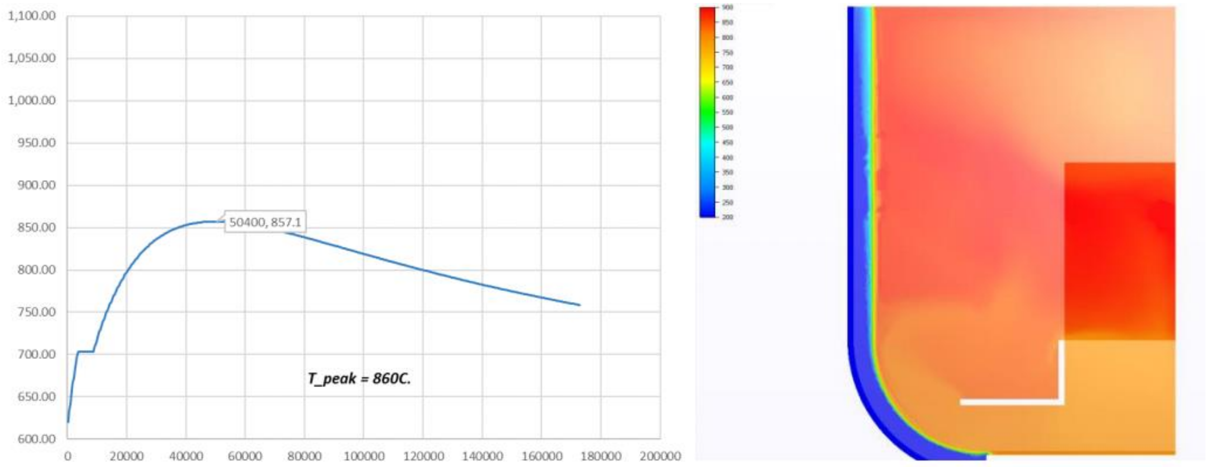


Figure 27: Moltex Energy's Passive Heat Removal Simulation (Moltex, 2018)

Continual Refuelling

Another feature of the SSR is its continual refuelling process to eliminate the requirement of outages, downtime, and refuelling where it could be generating electricity. The fuel pins are added at one end which hang from a support beam. Over time the fuel assemblies are moved in one direction that keep power and burn-up steady throughout the reactor.

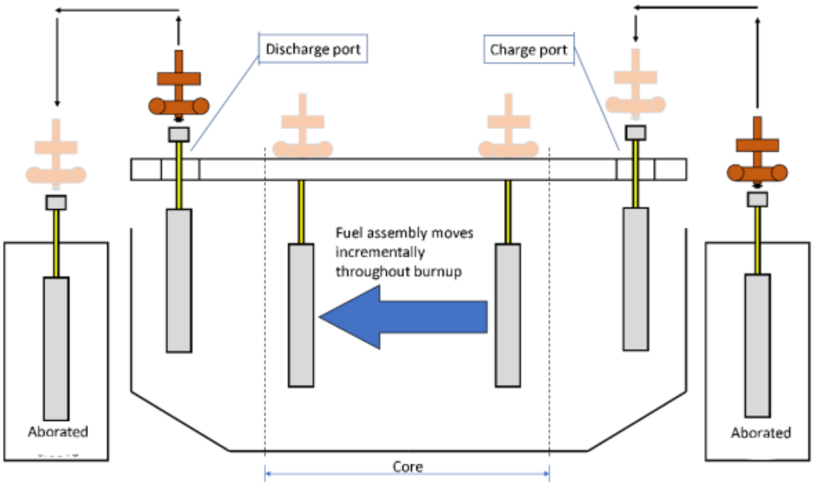


Figure 28: Moltex Energy's Continual Refuelling Process (Moltex, 2018)

One problem of the PWRs and small solid fuel modular reactors is that they are designed for a singular operation power output. Moltex Energy overcomes this by making the SSR a modular design, in which the modules can be conjoined for a scalable power output that meets a variety of customer demands. Each module has an electric output capacity of 150MWe, up to 8 of these modules can be placed in single reactor tank increasing output to 1200MWe as demonstrated in figure 30.

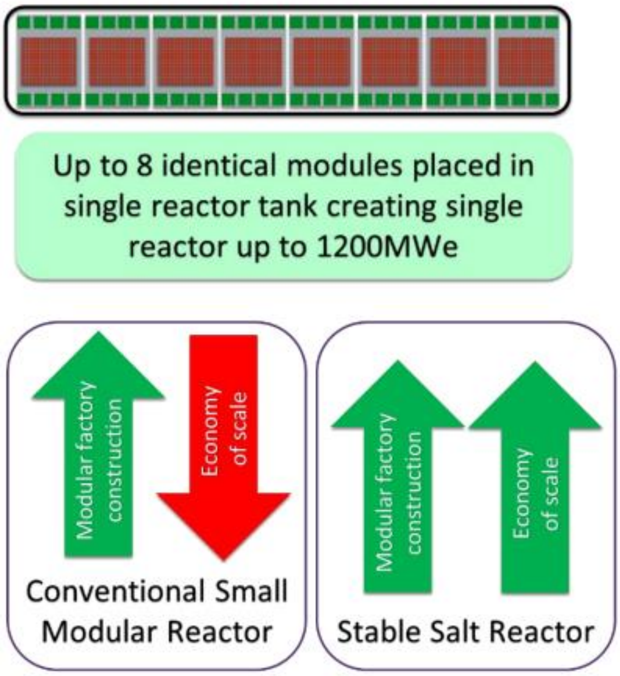


Figure 29: Moltex Energy's Economic Benefit of Modular Reactor Design (Moltex, 2018)

Economic Benefits

Modular construction of nuclear reactor is one of the most important aspects of decreasing capital costs. Most components of PWRs now are made outside of the UK due to no UK suppliers being obsolete since the 1970's. PWR components are generally much larger and heavier as the vessels must be designed to have thicker walls to contain with the vast pressures involved. This drives up cost as most parts must be imported through over-seas shipping, yet are too large to be placed inside shipping container which is both inconvenient and also increases risk of damage to the parts. The small modular reactor design benefits from the following (Moltex, 2018):

- Financing cost reduction – a shorter design and construction period means lower overall borrowing and lower financing costs for this borrowing.
- Off-site construction – the reactor is constructed offsite where there a fewer constraints (for example with tooling access, or physically with other companies operating on the same site). The constructor can also benefit from operating out their typical factory set-up, i.e. with the equipment and skills in situ.
- Modularisation – reactors are built in smaller modules that can be constructed several times over. This yields economy of scale in terms of the knowledge and experience gained from one module to the next and in the materials used for the reactors, which can be brought in on a greater scale than if it were a bespoke reactor.
- Digitising line management – the production line for parts in the reactor is digitised streamlining it and ensuring maximum efficiencies.

2.5) Spent Fuel

Argonne National Laboratory Research

Researchers at the Argonne National Laboratory pioneered the development of pyroprocessing, a high-temperature process for recycling spent nuclear waste into fuel. It allows 100x more of the energy that's currently utilised in commercial thermal reactors, therefore ensures a virtual inexhaustible supply of low-cost uranium. It is most important to reduce the volumes of spent nuclear fuel, as it capable of almost entirely separating the uranium and transuranics from fission products. Fission products are highly radioactive, which is directly proportional to its half-life. I.e. the more radioactive a substance is, the faster it decays thus shorter its half-life is. All fission products are so radioactive that they decay down to normal background levels of radiation in as little as 300 years. This means if all fission products were to be isolated from spent fuel, the resulting nuclear waste could be stored geologically from approximately 300,000 years to approximately 300 years. This is highly sought after as it is widely known that humans can build structures to last as long as 300 years, but not as long as 300,000 years. (ANL, n.d.)

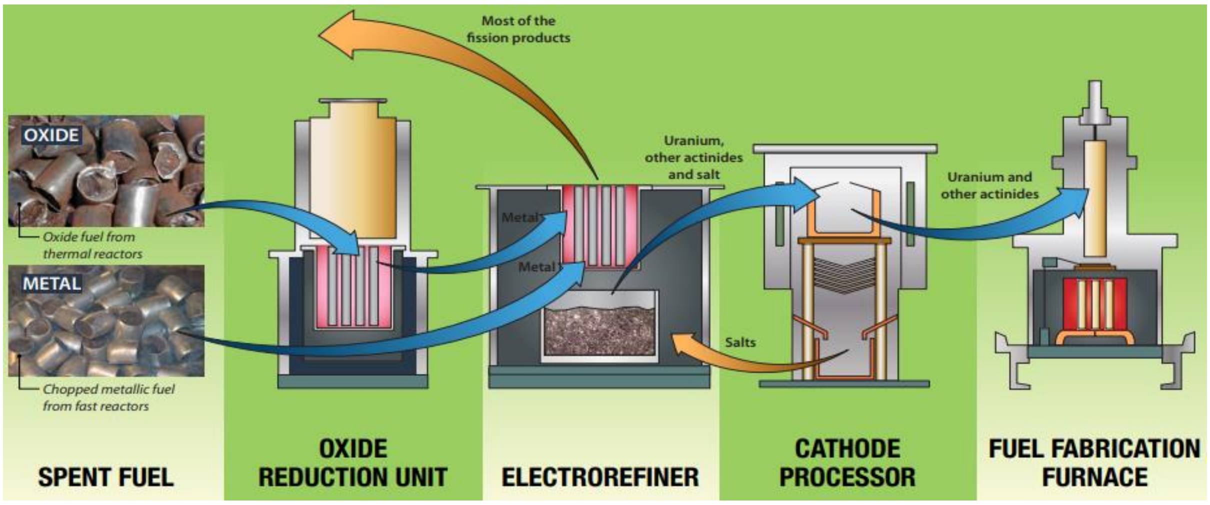


Figure 30: Argonne National Laboratory's Spent Fuel Process (ANL, n.d.)

The electrorefining process is key to the recycling process, it eliminates the complex addition of chemicals and solvents used in traditional fuel aqueous reprocessing (currently used at Sellafield). Electrorefining is very similar to electroplating, the spent fuel is converted to its metallic form and added to a vat of molten salt where it is dissolved. An electric current is passed through the vat, where most of the fission products plate out on the anode, and the uranium and other heavy actinide (plutonium, americium, neptunium etc) plate out on the cathode. It is then sent to the cathode processor where residual salt can be recycled back to the electrorefiner. Finally, the remaining uranium and actinides are cast back into fuel rods.

If these steps are implemented on a nationwide scale and the reprocessing cycle is repeated enough times, nearly all actinides will have been fissioned, leaving only short-lived fission products which can be easily stored due to reduction in volume and with its faster rate of decay.

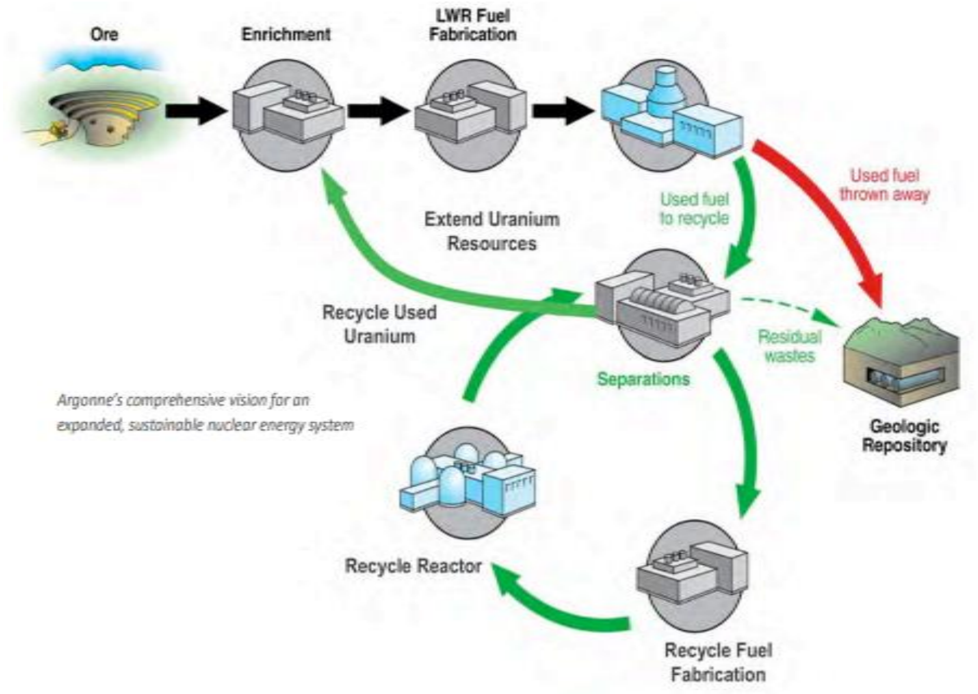


Figure 31: Argonne National Laboratory's Sustainable Plan for Future Fuel Cycle (ANL, n.d.)

Moltex Energy’s Spent Fuel Proposal

Current spent fuel reprocessing and temporary spent fuel storage in the UK takes place at Sellafield. The spent fuel rods are placed in deep water pools that act as an effective barrier for radioactivity, protecting the surrounding atmosphere from the escape of any radioactive material. Sellafield has aged and are now proving difficult and costly to manage, spending £3bn per annum for management of the site. Current spent fuel reprocessing at Sellafield uses aqueous dissolution techniques which removes fission products and blends the small amount of plutonium that is produced in thermal reactors with uranium. The new reprocess fuel that contains plutonium and uranium is called Mixed Oxide fuel (MOX) can then be re-used as fresh fuel in thermal reactors – solid fuel reactors use oxide forms of the fuel instead of the metallic form as it has a higher melting point.

Another option for spent fuel other than reprocessing and temporary storage is deep geological repository storage. The sites are purpose built in depths up to 1000m for storage flasks of spent fuel that have been vitrified – a process that transforms waste into a ceramic glass form so that possibilities of leakages are greatly reduced.

The new reprocessing technique developed by the Argonne National Laboratory, but re-invented, altered and patented by Moltex called WATTS (a form of pyroprocessing) involves removing the zirconium fuel cladding and fluorination it, converting to zirconium fluoride to be reused in the coolant salt. The declad fuel pellets contain fission products, fertile and fissile uranium, and long-lived actinides (plutonium) and dissolved in a molten salt and an electric current is passed through it. Major fission products; caesium, strontium, and iodine remain in the molten salt. The negatively charged electrode reduces the uranium, plutonium and noble metal fission products (which are ions within the salt) into a molten uranium alloy.

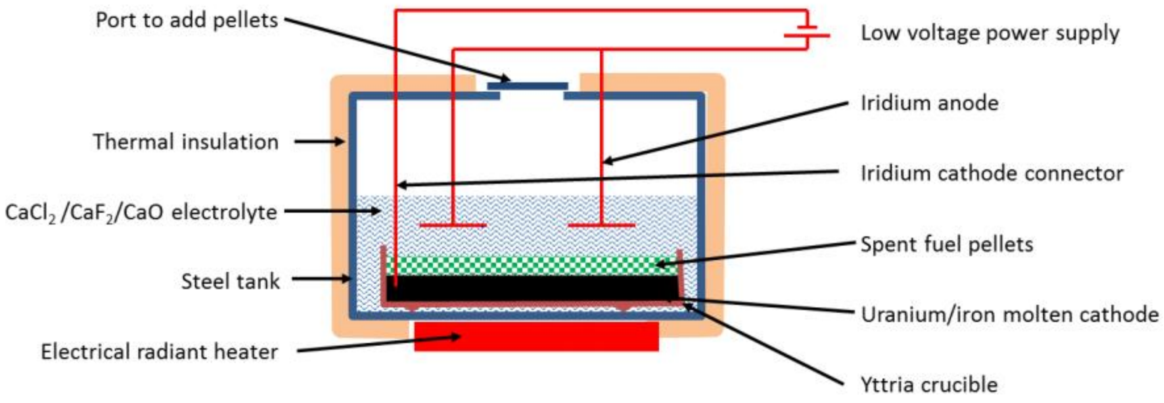


Figure 32: Moltex Energy's Patented Fuel Reprocessing Unit (Moltex, 2018)

The uranium alloy is then contacted with a clean sodium/iron chloride salt to make the fuel salt through exchange of iron chloride with plutonium, higher actinide (isotopes and elements with great mass than Pu-239 and noble metals, removing them.

The remaining uranium alloy is sufficiently free of long-lived actinides to be re-used for breeding purposed. This WATSS technique is very compact compared to standard aqueous processing that is carried out at Sellafield, where the size of the reprocessing plant is the same as a football pitch – WATSS would be the size of billiard table ($2m^2$ by $2m^2$), reducing costs and would be capable of processing 170 tonnes per year.

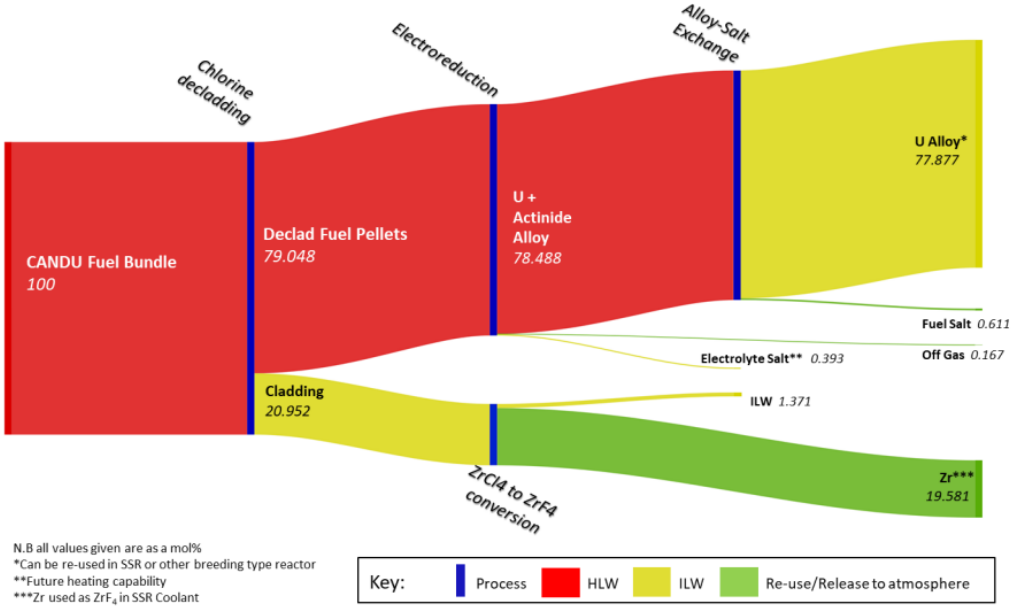


Figure 33: Moltex Energy's Spent Fuel Process (Moltex, 2018)

2.6) MSR Summary over PWR

A nuclear reactor that displays inherent safety features has always been a fantasy of reactor designers. With PWRs and all other types of solid fuel reactors, the definition of safety is mainly considered that the reactor can prove to maintain the fuel pellets in its solid state and within the cladding throughout as many potential emergency scenarios as possible. This is ultimately reversed in MSRs; having the fuel in a liquid state produces a system that has inherent safety. The MSR is self-regulating, its full passive design features depend on physical phenomena and not on the function of engineered systems and components. It instead relies on convection, gravity, negative temperature coefficient and high-temperature resistance; minimising human control and interference, making the design ‘walk away safe’. No other reactor that contains solid fuel can achieve this. With new methods of processing spent fuel, once separated, the un-reusable waste occupies far less volume than current waste due to utilisation of U-238, and can be stored for as little as 300 years.

(3) LITERATURE REVIEW – SOLAR TWO PROJECT

3.1) Introduction

An alternative concept for solar power is using the thermal energy provide by solar rays rather than utilising the photoelectric effect to induce an electric current over semi-conductor. Photo-Voltaics (PVs) will still be relevant technology used in the future, as they convert sunlight directly to DC current which is highly useful for powering most electronic devices. Most electronic devices use DC current, therefore the requirement of complex AC-DC converters that have certain losses are not needed. PVs have seen a vast decrease in capital costs since they were first introduced into the global market in early 2000's. Simultaneously, the efficiency has vastly increased vastly over the same time period from ~10% to ~30%. That being said, by using first principles and a hypothetical approach, if PVs in the future were to achieve 100% efficiency, they would extract a theoretical maximum of 1000W/m^2. With 100% efficiency PVs, it would require 1,000,000m^2 of land to produce the same output as a typical 1GWe nuclear power plant which requires only 500-1000m^2. PVs also have the major disadvantage that they can only produce power when there is available sunlight which is not available constantly throughout a 24hr day period.

The purpose of solar thermal plants is that they can overcome the intermittency problem by using tracking heliostats (mirrors) to reflect the solar rays into one concentrated spot (the solar receiver) to achieve a maximum possible temperature. The solar receiver heats a molten salt to ~565°C when it is transferred to an insulated storage tank called the hot salt storage tank.

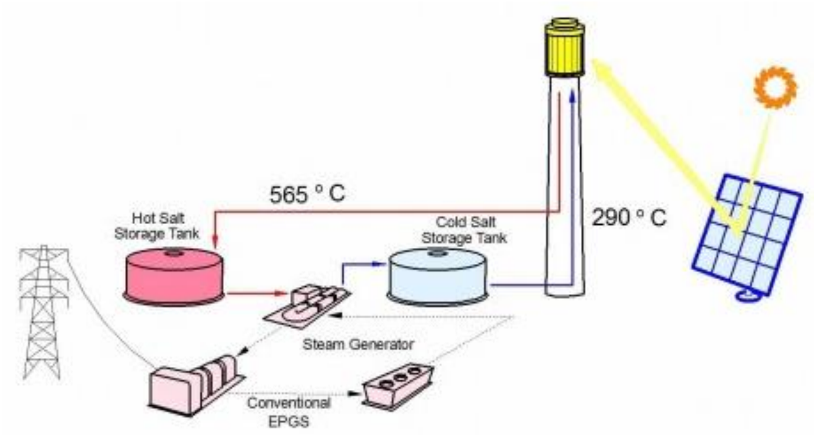


Figure 34: Thermal Solar Plant Schematic (Bradshaw, et al., 2002)

When power is needed throughout the 24hr day period, the 565°C molten salt is pumped to a heat exchanger to generate steam that powers a turbine as shown in figure 36. This enables the plant to produce power during day, through clouds and at night, independent of solar collection. After salt transfers most of its thermal energy to the steam, it returns to the cold salt storage tank. When there is sufficient sunlight to heat the cold salt back to 565°C, it is pumped back to the solar receiver to continue to cyclic process.

The most beneficial aspect of concentrated solar thermal plants over conventional PV is that the power output can be controlled.

3.2) Common Safety and Technical Advantages with the Solar Project

Properties of molten salt

Using molten salts enables all the plant equipment (i.e. pipes, valves, heat exchangers and storage tanks) that circulates and transfers the very high-temperature salt to be much thinner and reduces complexity of the design. This is because the thermophysical properties of a molten salt are that they have a very small vapour pressure right up to its high boiling point, this is a property most other organic and non-organic liquid (water and oil) do not have. Molten salt is highly thermally stable. (Bradshaw, et al., 2002) The nitrate salts used in the Solar Two Project are also non-toxic.

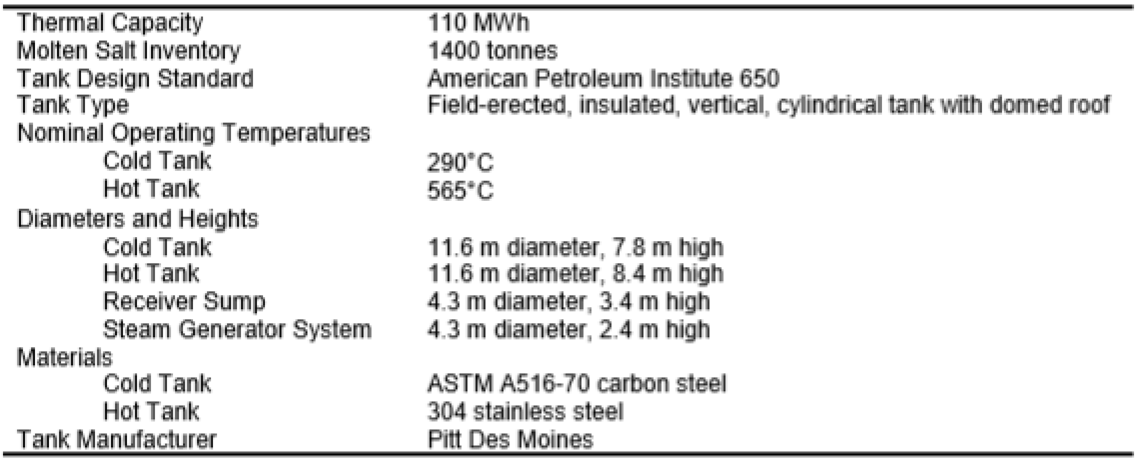
Thermal Storage System

Both storage tanks were constructed from carbon and stainless steel due to their high corrosion resistance to molten (nitrate) salt and each were sized to hold the entire inventory of salt.

Figure 35: TS Tanks from the Solar Project (Bradshaw, et al., 2002)

The tanks gravity fed the salt to sumps were the pumps were located and the level of the salt were measured with bubble level detectors. Levels of the salt were maintained in each tanks through the level detectors which modulated a control valves at the outlet of that tank to maintain the prescribed level.

The cold tank and hot tank contained two and three 25kW-e heaters respectively to maintain the salt at a minimum temperature of 290°C to prevent the salt solidifying when the plant experienced an outage and was down for repairs. The sides and the roof of the cold tank was insulated with 23cm and 15cm of mineral wool blankets overlaid with 5cm of fibreglass boards. Similarly, the sides and the roof of the hot tank was insulated with 46cm and 30cm of mineral wool blankets, again overlaid with 5cm of fibreglass boards was insulted The external walls of the tanks were then covered with aluminium jackets for weather protection. The bottom of the cold and hot tank was insulated with 41cm and 30cm of foam glass respectively. (Bradshaw, et al., 2002)



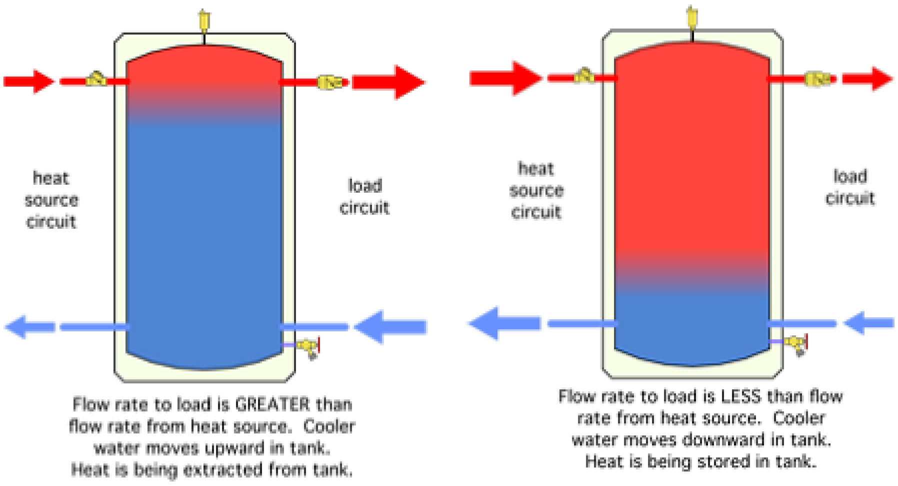
Thermal Capacity	110 MWh
Molten Salt Inventory	1400 tonnes
Tank Design Standard	American Petroleum Institute 650
Tank Type	Field-erected, insulated, vertical, cylindrical tank with domed roof
Nominal Operating Temperatures	
Cold Tank	290°C
Hot Tank	565°C
Diameters and Heights	
Cold Tank	11.6 m diameter, 7.8 m high
Hot Tank	11.6 m diameter, 8.4 m high
Receiver Sump	4.3 m diameter, 3.4 m high
Steam Generator System	4.3 m diameter, 2.4 m high
Materials	
Cold Tank	ASTM A516-70 carbon steel
Hot Tank	304 stainless steel
Tank Manufacturer	Pitt Des Moines

Figure 36: TS Tank Data (Bradshaw, et al., 2002)

Above in figure 38 is the technical characteristic of the thermal storage system. To reduce heat losses as the tanks were charged and discharged, piping was connected to the vents of the two tanks so that air inside (at atmospheric pressure) would not exchange with the cooler outside ambient air. This piping was also insulated to reduce heat loss. Connected the ullage air of the two tanks allows for the levels in each tank to independently change without causing pressure differences within them, therefore reduces complexity of the design.

Type of TS Tank

In this configuration, avoiding the more conventional approach to storing thermal engineer in a stratified tank as shown in figure 39:

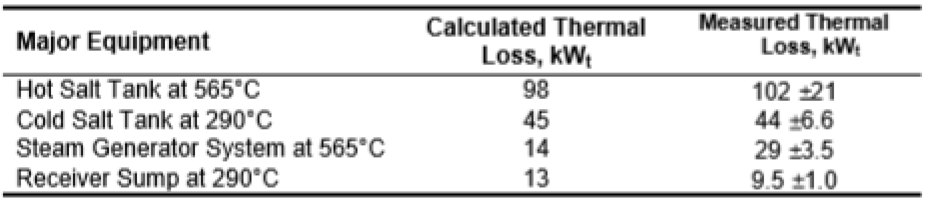


Flow rate to load is GREATER than flow rate from heat source. Cooler water moves upward in tank. Heat is being extracted from tank.

Flow rate to load is LESS than flow rate from heat source. Cooler water moves downward in tank. Heat is being stored in tank.

Figure 37: Stratified Tank Charging and Discharging (Heatspring, 2016)

Stratified tanks contain the two bulk fluids, relying on the small density difference for separation. This is effective for small water boiler, commonly used for domestic applications. However, the two bulk fluids are still in direct contact, therefore heat transfer between the two mediums is greater than what it would be if they were in two separate tanks, as the thermal conductivity of water/molten salt is relatively high. Having two separate tanks reduces the temperature variance of the two fluid mediums, therefore reduces the complexity of the design of the entire system with regards to operating the heat source and flowrates for heat exchangers.



Major Equipment	Calculated Thermal Loss, kW_t	Measured Thermal Loss, kW_t
Hot Salt Tank at 565°C	98	102 ±21
Cold Salt Tank at 290°C	45	44 ±6.6
Steam Generator System at 565°C	14	29 ±3.5
Receiver Sump at 290°C	13	9.5 ±1.0

Figure 38: TS Tank Thermal Losses Data (Bradshaw, et al., 2002)

In figure 40, it is demonstrated that the measured heat loss of the storage systems is exceptionally low as predicted. This allows for far more efficient thermal energy storage. Based on the results of the solar project, it was expected that the annual efficiency of the thermal storage system in a commercial plant should be about 99%.

Steam Generating system

The steam generator is divided into the three main vessels; preheater, evaporator and the superheater, each of which is connected to a salt heat exchanger in a counter-flow type configuration. As the water enters the preheater, it absorbs heat from the last downstream salt heat exchanger, i.e. the lowest operating temperature heat exchanger. The evaporators operates at a higher temperature and pressure than the preheater and initiates the vaporisation process of water at 100 bar. The saturated water vapour then exits the evaporator and enter the superheater, converting it to superheated steam at 510°C. 510°C steam at 100bar is of a much quality than standard PWR’s steam generators, as the maximum operating temperature of a PWR is 315°C. Using higher temperature steam maximises lifespan of the steam turbine, as the steam is less likely to condense in the low-pressure blades, which greatly increases erosion rates.

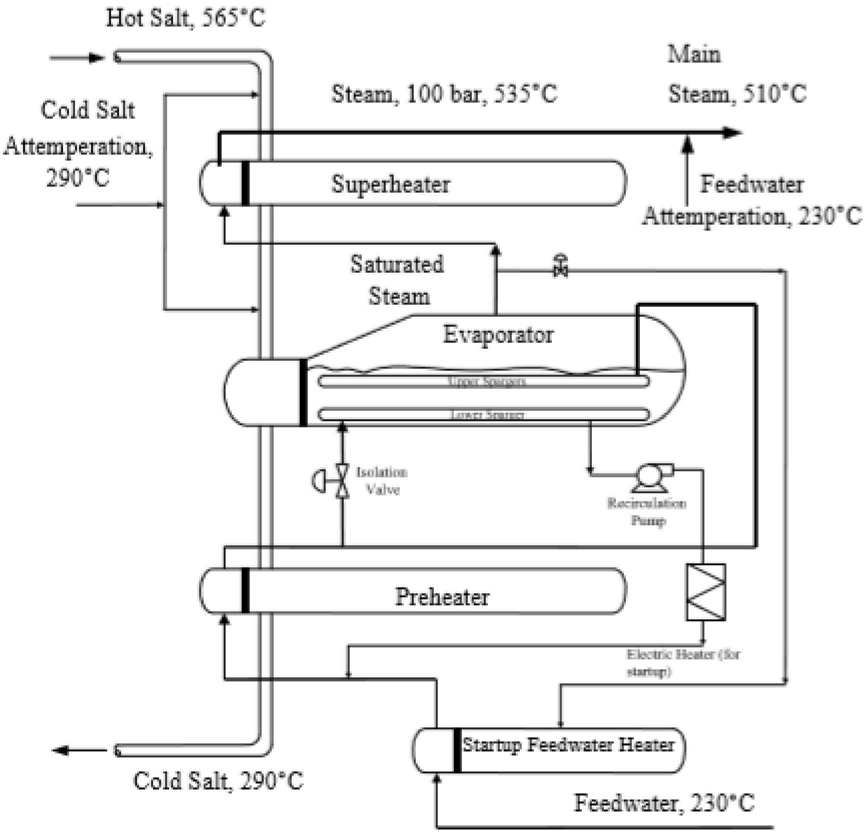


Figure 39: Steam Generator Layout (Bradshaw, et al., 2002)

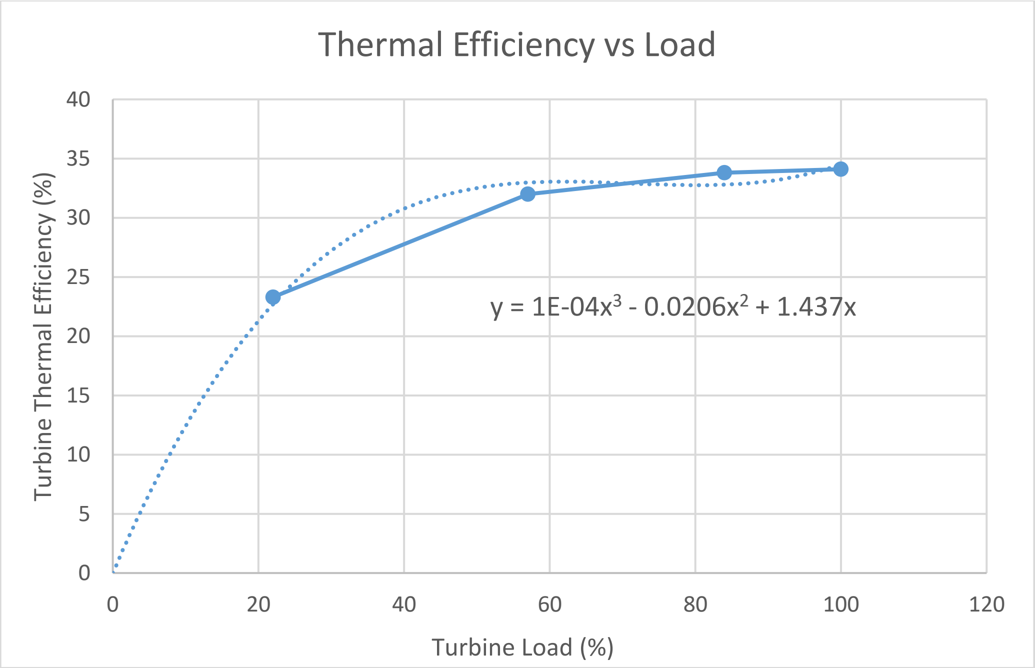


Figure 40: Turbine Efficiency vs Turbine Load (Bradshaw, et al., 2002)

Turbine load/thermal efficiency tests were carried out to analyse the performance of the steam turbine. Results were plotted as shown above in figure 42. A 3rd order polynomial trendline was added to the plots to predict thermal efficiencies at lower loads. From this equation, it is estimated that thermal efficiency drops to as low as ~12% if the load decreases to 10%. This exponential decrease was the justification for having two turbines operate as low as 25% load for the proposed system.

3.3) Challenges relevant to the MSR proposed system

Tank venting

The initial justification for using an insulated pipe could shuttle ullage air between the two storage tanks as they were continuously charged and discharges whilst reducing heat lost to outside ambient air. Although molten salt has very low vapour pressure, very small quantities of salt vapour were still generated. As soon as the vapour come into contact with a cold spot they freeze. This created problems in the tank vent pipe itself and was overcome by continuously using an electric heater within the pipe. Throughout normal operation conditions, it was observed that the electric heater consumed more thermal energy that what would have been saved by shuttling the air. This can be solved by simply exchanging air with the outside ambient air, or through installing expanding insulated tanks that can vary their volume – similar to how natural gas storage tanks operate. (Bradshaw, et al., 2002)

Salt Receiver

During normal operation and nightly shutdown of the plant, the solar receiver drained the remain salt back to the cold tank. Small quantities of salt were observed to freeze in the piping and valves due to the temperatures falling beneath the melting point of 200°C. Special thawing panels were required to carefully heat the salt to melt it for drainage. These problems would not exist if the heat source from the solar receiver was maintained at its constant normal operating conditions. Therefore it can theorized that replacing the solar receiver with a constant heat source, such as a nuclear reactor, this too would vastly improve the salt-freezing problems. (Bradshaw, et al., 2002)

(4) UK NATIONAL GRID ANALYSIS

The UK's electrical supply and demand was analysed over two separate days; one that had the lowest peak electrical demand and one that had the highest peak demand throughout the year. Data collected on the two days were on the 17th of June and 1st of March 2018 shown in figure 43 and 44. This was done to demonstrate the vast difference in electrical power generation and consumption over two days in two different seasons.

As shown, the UK minimum demand for electricity in 2018 so far was as low as 19.427GW one the 17th June, yet the maximum was more than double this at 50.376GW occurring on the 1st of March. (Statistics, 2018) The massive discrepancies in the overall power generation is explained by higher electrical power being consumed in the cold winter months to provide domestic, industrial and commercial electrical heating and lighting.

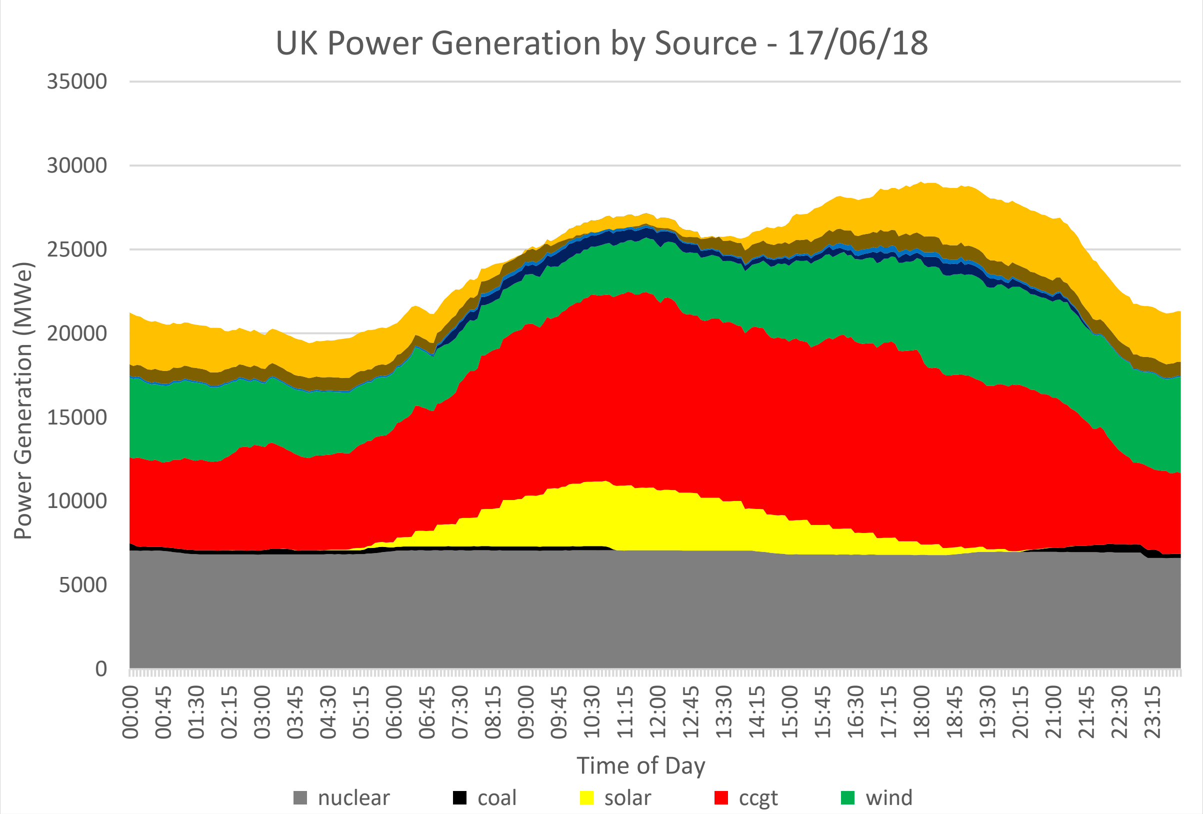


Figure 41: UK Minimum Electrical Power Demand & Generation by Source (Statistics, 2018)

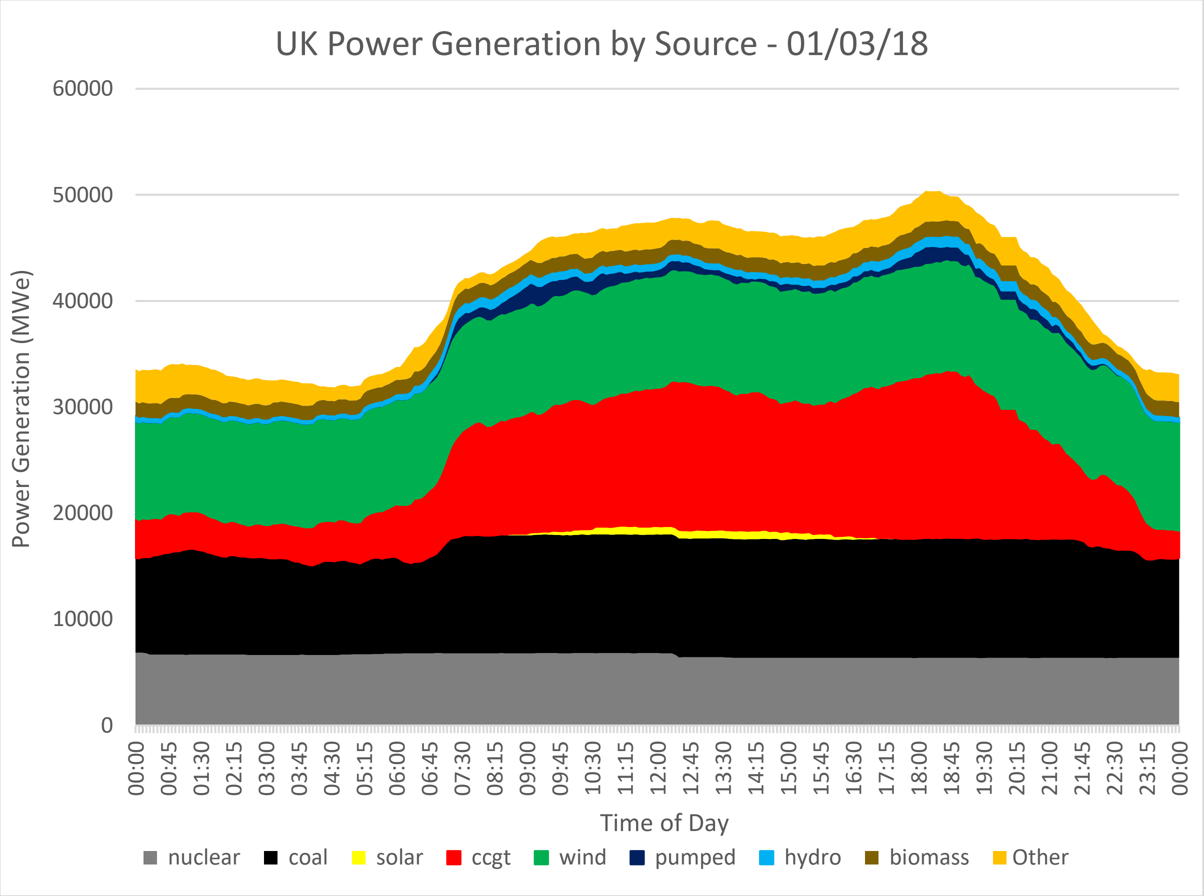


Figure 42: UK Peak Electrical Power Demand & Generation by Source (Statistics, 2018)

It is clear through visual representation in figure 43 and 44 that in both days that CCGT generation provides the most flexible power output than any other generation source.

(5) PROPOSED SYSTEM + MODEL

The proposed system to be modelled was to replicate the generated power that was provided by CCGT plants on the 17th of June and the 1st of March. However, figures x and x show the entire country's CCGT make up which includes 33 plants, most of which containing more than one gas turbine.

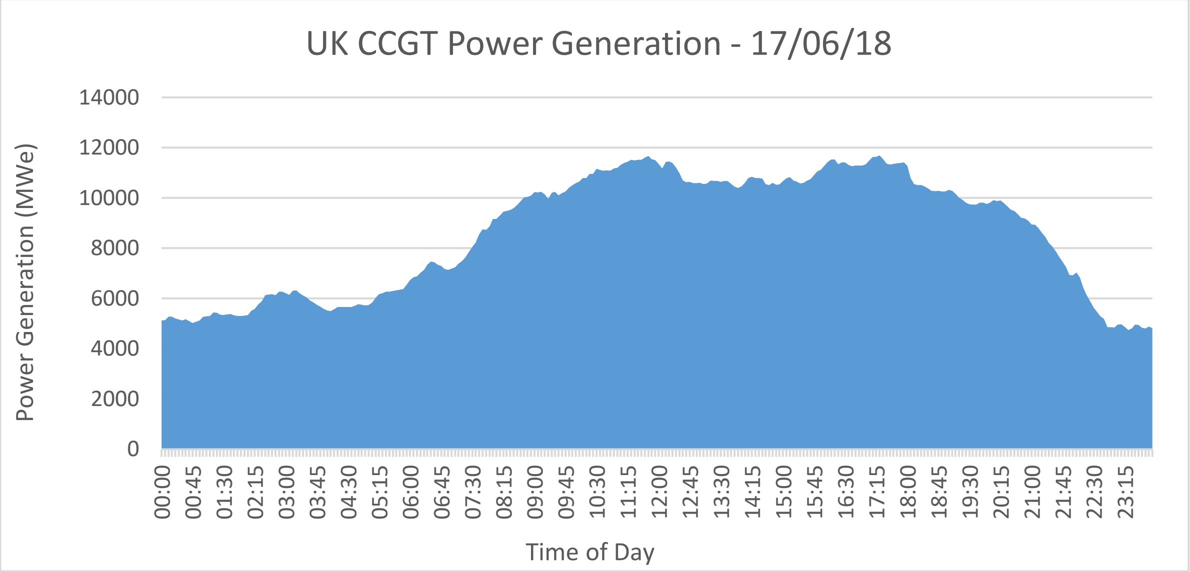


Figure 43: UK Minimum Electrical Power Generation of CCGTs (Statistics, 2018)

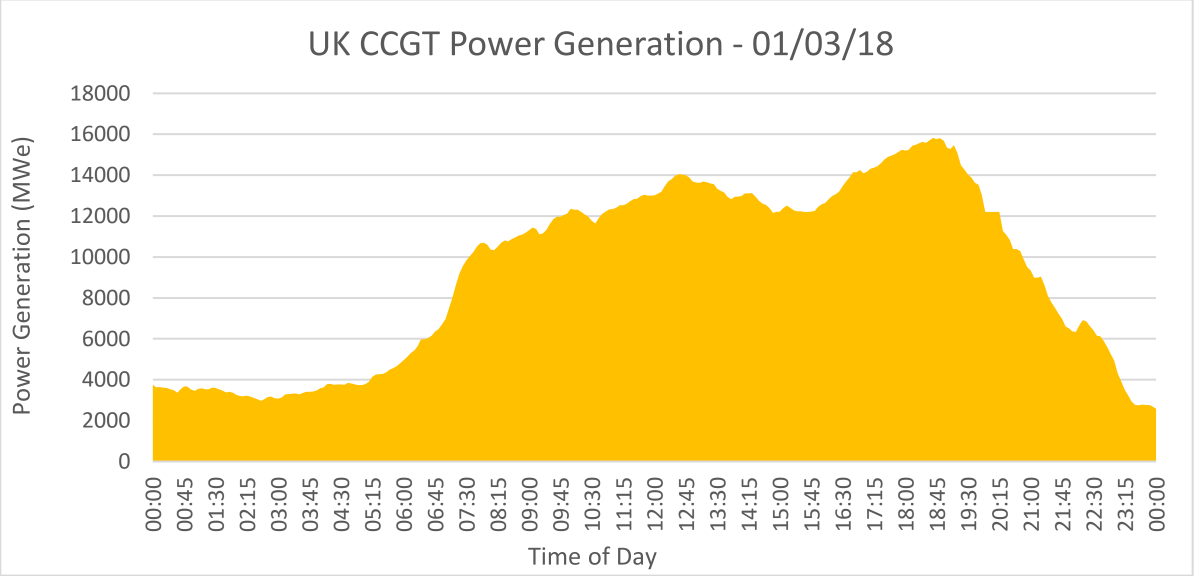


Figure 44: UK Peak Electrical Power Generation of CCGTs (Statistics, 2018)

It can be seen from these figure 45, 46 and is shown again in table 3, a minimum and maximum power output from the entire country's CCGT fleet both in March.

	Table 3			
	Time	Direct Data from 33 CCGT Plants (MWe)	Proposed System (MWe)	Fraction of Peak Power
Peak Generation Output	18:40 (March)	15820	1582	1.000
Lowest Generation Output	23:55 (March)	2690	269	0.170

For the purpose of this project, the CCGT profiles on both days were scaled down by a factor of ten to model a singular power generation system. This was done to prove that one singular system could provide the same flexibility of output and dynamic behaviour that the entire UK fleet currently provides i.e. the system must be able to produce a maximum output of 1582MWe yet can also provide an output as low as 296MWe.

Steam turbines provide mechanical rotational energy to the generator that allows it to convert the initial thermal energy from the steam into final electrical energy for consumer use. They can vary the electrical power output by varying the steam flowrates relative to magnetic field strength over the generator stator coils. Typically, steam turbines in fired boiler plants have to operate as low as 5% of their maximum possible load, however operating as low as 10% drastically reduces thermal efficiency of the cycle. To reduce the effects of lower thermal efficiencies the modelled system uses two steam turbines; essentially two Rankine cycles are installed which operate at a minimum of 25% of their maximum load. Having this set-up provides much greater flexibility of what the system can generate. This is demonstrated below in table 4 when the maximum designed load of each turbine is 800MWe:

Table 4					
Turbine Output (fraction)	1.00 1.00	0.75 0.75	0.50 0.50	0.25 0.25	0.25 0.00
Turbine 1 (MWe)	800	600	400	200	200
Turbine 2 (MWe)	800	600	400	200	0
Turbine 1 + 2 (MWe)	1600	1200	800	400	200
Plant Capacity (MWe)	1600	1600	1600	1600	1600
Capacity fraction	1.00	0.75	0.50	0.25	0.125

This set-up is ideal as a capacity fraction of 0.125 of the total possible output is within the capacity fraction range taken from the CCGT data which is 0.170.

This creates a secondary problem with regards to plant operation, due to varying the steam flowrates to each of the steam turbines. This presumes that heat taken from the boiler/heat source would also vary accordingly to the heat required to be transported to the turbines. This is done easily and regularly in coal and gas plants by adding more or less fuel to control combustion rates but is avoided as much as possible with nuclear reactors. Typically, the capital cost of a nuclear reactor and the reactor heat exchangers are far higher than that of a coal furnace and boiler. This is because all components and materials in the reactor have to withstand extreme conditions of radiation as well as the enhanced safety control systems in place which have to all be checked by the nuclear regulators.

Nuclear reactors have to operate far longer than gas turbines and coal furnaces as they must be able to sell electricity at a specific price per unit of energy over its operational lifespan that will pay off their initial higher capital costs over a certain period, and then to start generating profit to make the entire project worthwhile in the first place. Frequent and large fluctuations in the thermal power extracted from the reactor creates a lot of unwanted thermal stress within the reactor and its components which vastly decreases plant operational lifespan. Currently, the nuclear energy sector avoids as much as possible, although in some countries with high proportions of electricity being generated by nuclear plants such as France, have to make their plant load-follow. This problem is overcome by using a tried and tested component currently used in solar thermal plant technology.

Solar thermal plants use concentrated thermal solar energy to heat a molten salt to ~600°C in a 'solar receiver', which is then stored in a 'hot' storage tank. When energy is required the 'hot' molten salt is pumped to a heat exchanger/steam generator where it generates steam to power a steam turbine for electricity production. The 'cold' salt exits the steam generator after transferring its thermal energy and returns to a 'cold' storage tank ready to pumped back into the solar receiver when there is sufficient solar energy available.

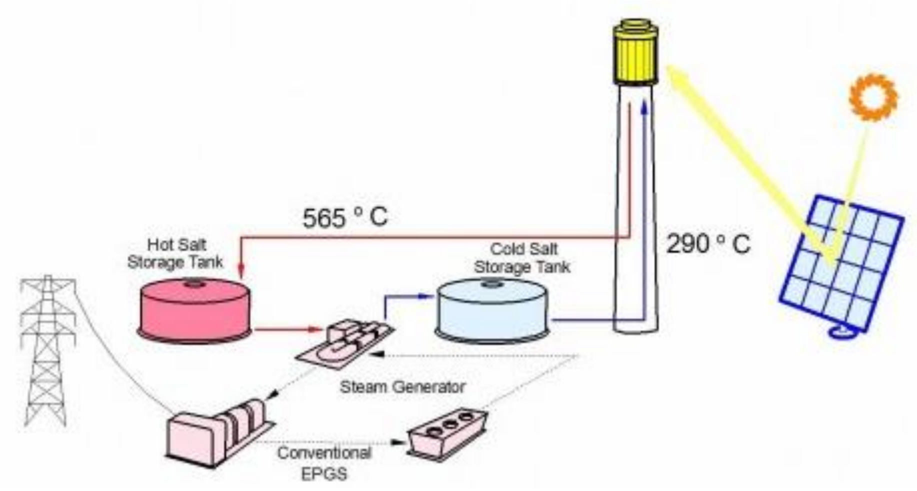


Figure 45: Solar Thermal Plant Schematic Diagram (Bradshaw, et al., 2002)

In the proposed system, pumps regulate heat extracted from the molten salt reactor instead of a solar receiver which decreases the fluctuation in power and temperature operation of the reactor, thereby vastly reducing thermal stress of the internal reactor components. This, therefore, increases plant lifespan and decreases the cost of electricity per unit of energy relative to conventional nuclear plants. (Mohanty, et al., 2016)

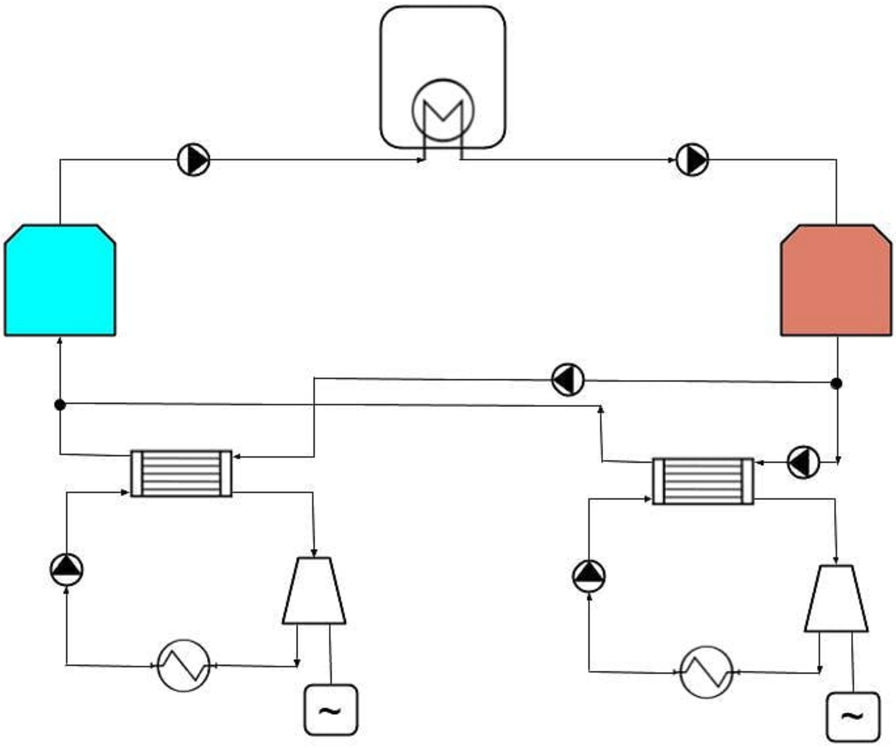


Figure 46: MSR & TS System Schematic Diagram

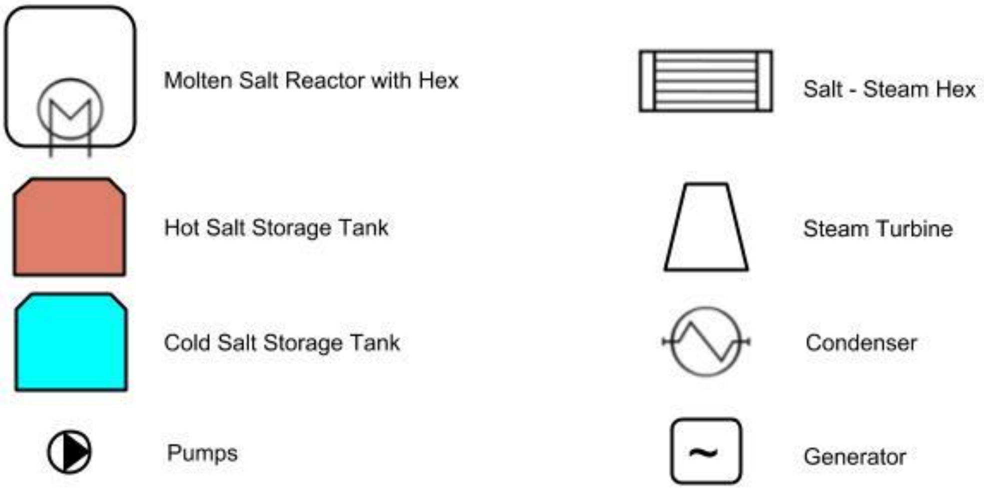


Figure 47: Key for MSR & TS System Schematic Diagram

(6) RESULTS & DISCUSSION

Tabulated data was collected from gridwatch to build a model that represented all 33 CCGT plants in the UK. The total power they generated to supply the electrical demand on a 5-minute basis was recorded over each day on the 17/06/18 and 01/03/18. This was the known quantity of electrical power that the proposed model would have to generate through its steam turbines per 5 minutes for 24 hours shown in figure 50 for the 17th of June.

6.1) Power Requirement Findings

This quantity of electrical power could be used to determine the thermal energy from the steam required to power turbines by assuming the thermal efficiency of the turbine. It was assumed that the steam turbines thermal efficiency remained constant at 41% throughout their 25-100% load range. Justification for this is later discussed in the results section.

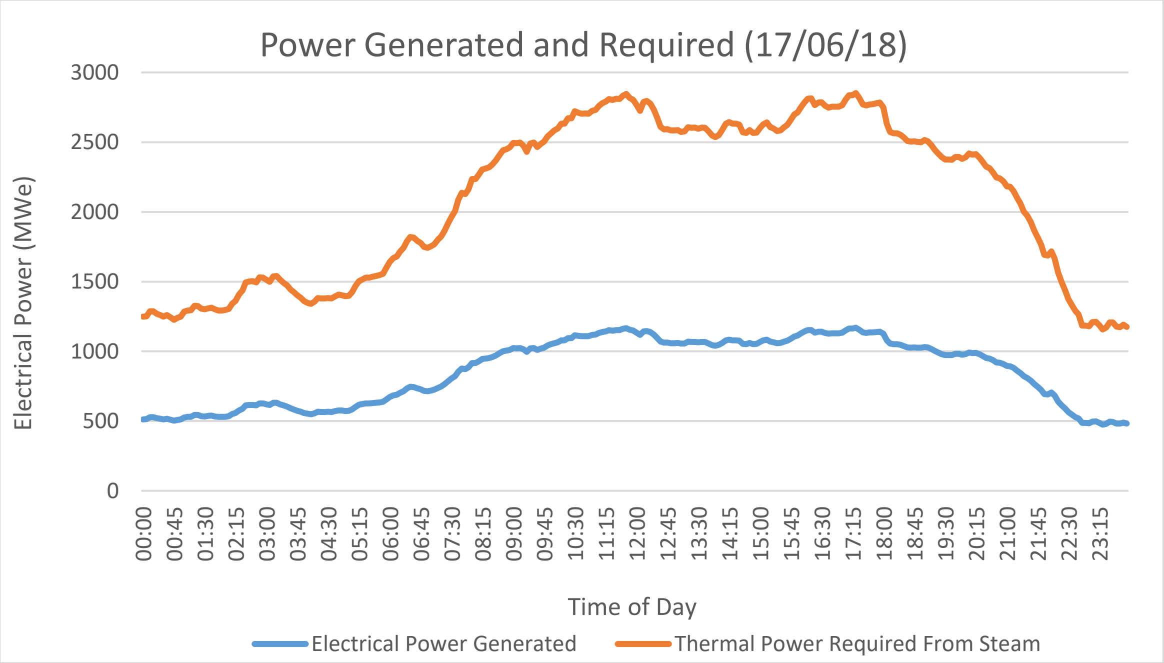


Figure 48: Power Required from Salt with Electric Power Generated from Turbines

The thermal power required from the salt – steam heat exchanger (steam generator) was determined by assuming the total effectiveness of the steam generator. This was done by taking the average efficiencies of each component within the steam generator and was found to be 71.7%. Thermal power required from the hot molten salt to the steam generator is shown in figure 50.

The thermal energy required from the salt would be straight from the hot salt tank kept at 565°C. The temperature of the salt kept in the storage tank was 290°C, therefore, an energy mass balance could be solved to find the flow rates of hot salt required to the steam generator. As shown in figure 51 the total flowrates of hot salt were found through Eqn. (1):

$$\dot{m}\left(\frac{kg}{s}\right) = \frac{Q\ (MWth)}{C_p\left(\frac{kJ}{kg\ K}\right)(T_{hot\ salt} - T_{cold\ salt})(K) \times 1000\ \left(\frac{MJ}{kJ}\right)} \tag{1}$$

Where ṁ is the mass flowrate of salt through the steam generator(s), Q is the thermal power required to generate steam, C_p is the specific heat capacity of salt and dT is the difference in temperature of the salt entering the steam generator(s) from the hot tank and the of cold salt exiting the generator which enters the cold tank.

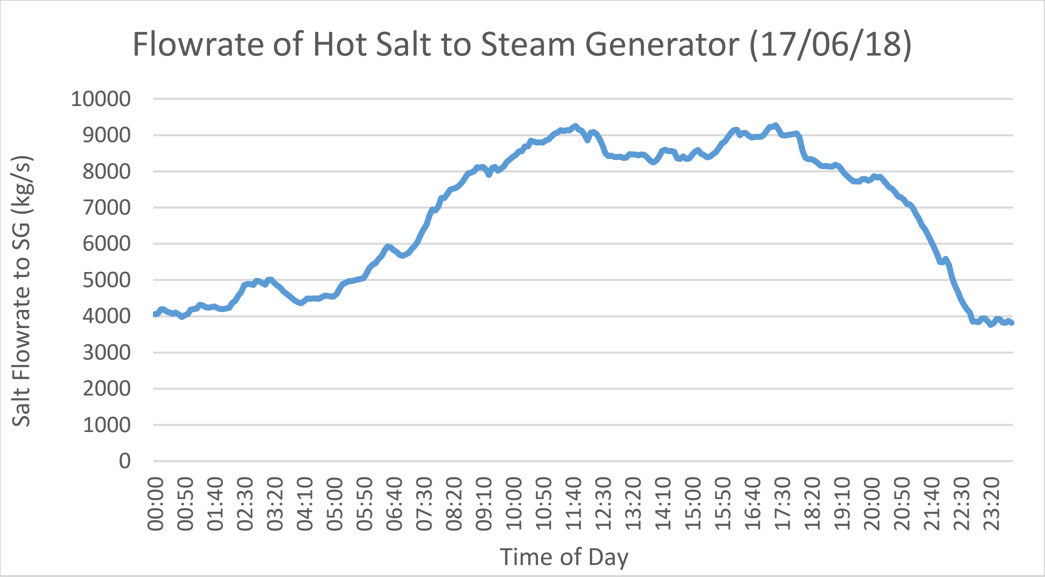


Figure 49: Salt Flowrate to Generator

Once the salt flowrate to the steam generator was established an accumulation balance was carried out to find the size of the tanks required. The hot tank mass balance is a shown below in Eqn. (2):

$$Accumulation\ of\ salt\ \left(\frac{kg}{s}\right) = Hot\ salt\ in\left(\frac{kg}{s}\right) - Hot\ salt\ out\left(\frac{kg}{s}\right) \tag{2}$$

Where the accumulation of salt is the rate of which salt accumulates in the tank. When positive the tank fills and when negative the tank empties, i.e. the accumulation is the rate of which the tank fills or empties. The 'hot salt in' is the flow rate of salt from the reactor into the hot tank. The 'hot salt out' is the flow rate from the tank to the steam generator.

The hot salt flowrate into the tank was calculated through iteration by adding every recorded accumulation value of salt in the tank at each 5 minute period over the 24 hour day. The flow rate of the hot salt into the hot tank was kept constant throughout the 24 hours but was found by iteration until the total accumulation was made equal to zero e.g.

Table 5

Time	Salt in from reactor (kg/hr)	Salt out to steam generator (kg/hr)	Accumulation (kg/hr)
12:00	200	500	-300
13:00	200	100	100
14:00	200	0	200
		Total Accumulation (kg/hr)	0

A total accumulation mass flowrate of zero would imply that there was sufficient flowrate of hot salt entering the tank throughout the entire day to supply the total amount of salt being displaced within the tank to power the steam generator.

The flow rate of hot salt into the tank to keep the total accumulation at zero was found to be 6818.21684kg/s. For the winter model on the 1st of March, it was calculated to be 7346.5317kg/s. The charge, discharge and accumulation rates of the salt across hot tank are represented graphically as shown in figure 52 and 53.

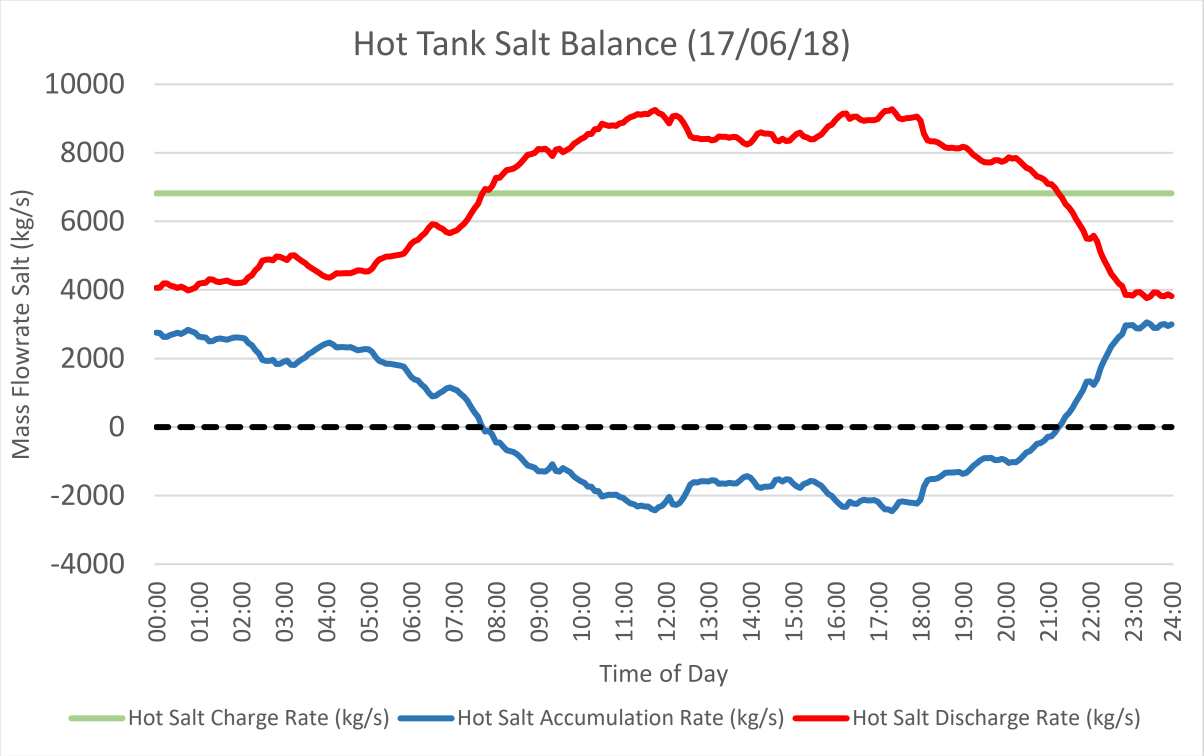


Figure 50: Hot Tank Salt Balance (17/06/18)

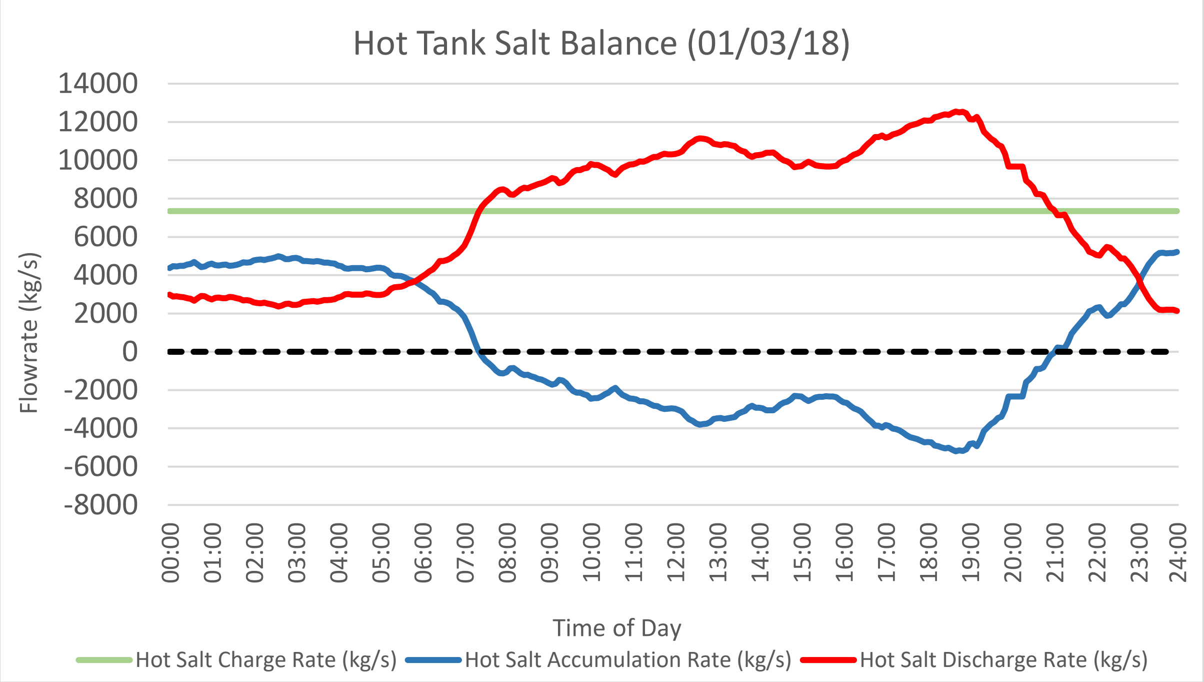


Figure 51: Hot Tank Salt Balance (01/03/18)

The constant flow rate of salt is the salt being pumped from the cold tank, through the reactor heat exchangers and back to the hot storage tank. As this flowrate is constant, the thermal requirements of the reactor is calculated through Eqn. (3):

$$Q = \dot{m}C_p dT \tag{3}$$

Where ṁ is the mass flowrate of salt, C_p is the specific heat capacity and dT is the difference in temperature of the salt exiting and entering the reactor. As the two temperature are known from the two desired temperatures of the storage tanks (290°C and 565°C) the thermal power requirement for the winter model was 3151.66MWth, summer was 2925.02MWth. This is a 7.19% change in relative thermal power output from the reactor, for two of the most extreme demand scenarios in the UK and well within the range of a MSR flexible power output as they have a range of 50%-150%.

As seen from figure 52 and 53, the accumulation rate becomes negative when the green charge rate line intersects the red discharge line. The largest negative accumulation rate is the theoretical largest displacement of salt in the tank. Therefore, to find the volume of tank required to operate the proposed system would be the largest volume that would be required to fill this largest displacement.

6.2) Tank Volume Requirement

All values were recorded within 5-minute intervals, the mass of salt required to be available in the tank would have to be calculated. This was found by multiplying the number of seconds within 5 minute by the mass flow rate as shown below in Eqn. (4):

$$Salt\ Accumulated\ in\ tank\ per\ 5\ minute\ interval\ (kg) = Accumulation\ \left(\frac{kg}{s}\right) \times 300\ (s) \tag{4}$$

$$Actual\ Salt\ in\ Tank\ (kg) = Salt\ Accumalted\ (kg) + Largest\ Salt\ Displacement\ (kg) \tag{5}$$

$$Volume\ of\ Salt\ in\ Tank\ (m^3) = Actual\ Salt\ in\ Tank\ (kg)\ \div Salt\ Density\ \left(\frac{kg}{m^3}\right) \tag{6}$$

The largest salt displacement during a 5-minute interval throughout the 24 hours was in the winter model and was found to be 1559328.3kg. This mass of salt had to be already within the tank for it to be available for powering the turbines throughout the date. To determine the actual size of the tank required the largest displacement was added to every 5-minute value, and the largest overall mass value could be found. The density of salt used within the thermal storage loop was 1680 kg/m^3, the largest mass value was 3123386kg, therefore, the largest volume of the tank required was 1859 m^3. This was larger than the largest volume required by the summer model which was calculated to be 984 m^3. Therefore the tank volume of each cold and hot are said to 1859 m^3, which has the cubic dimensions of 12.3m.

The volume of salt in the hot tank is as shown for both days is represented in figure 53 and 54:

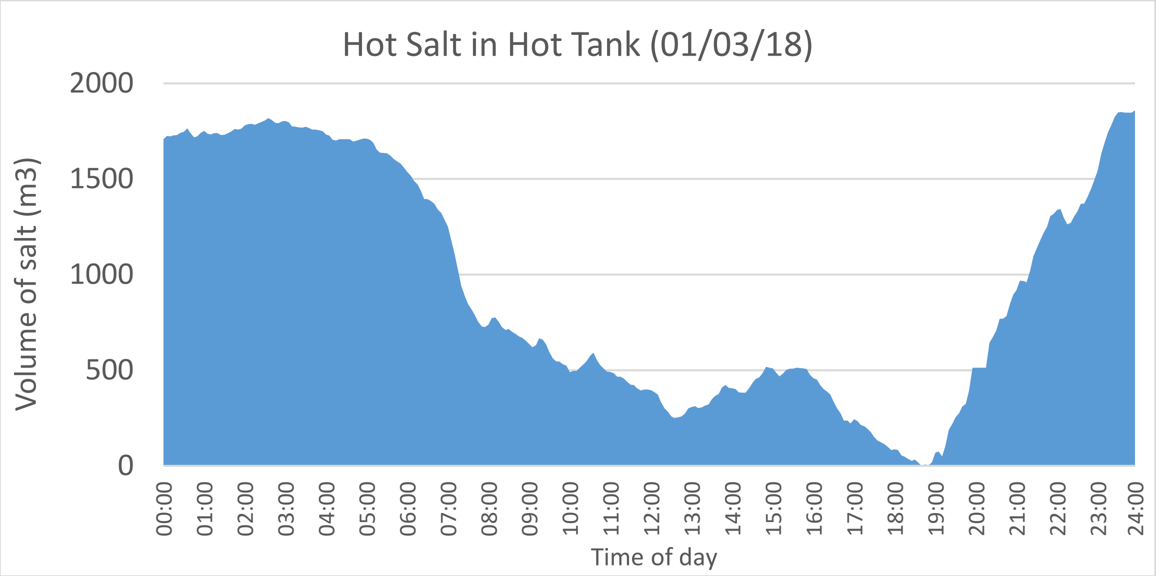


Figure 52: Volume of Salt in Hot Tank (01/03/18)

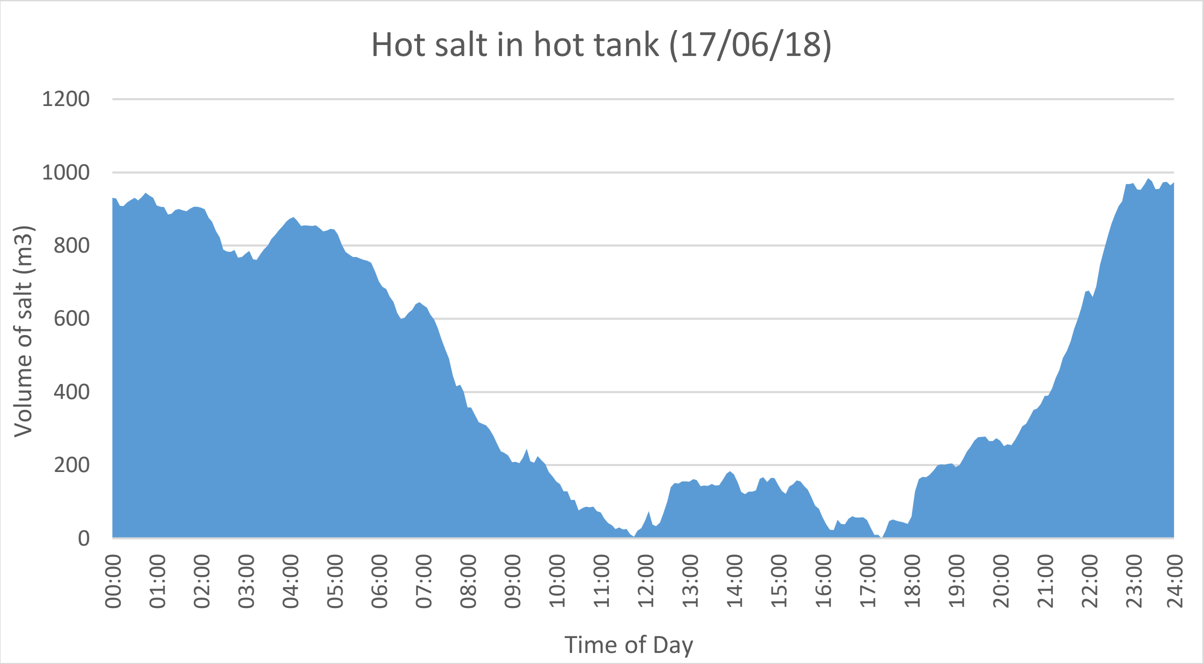


Figure 53: Volume of Salt in Hot Tank (17/06/18)

The volume in the cold tank is simply the maximum volume required by the hot tank, minus the volume of salt in the hot tank at each time interval as is shown below in figure 55 and 56:

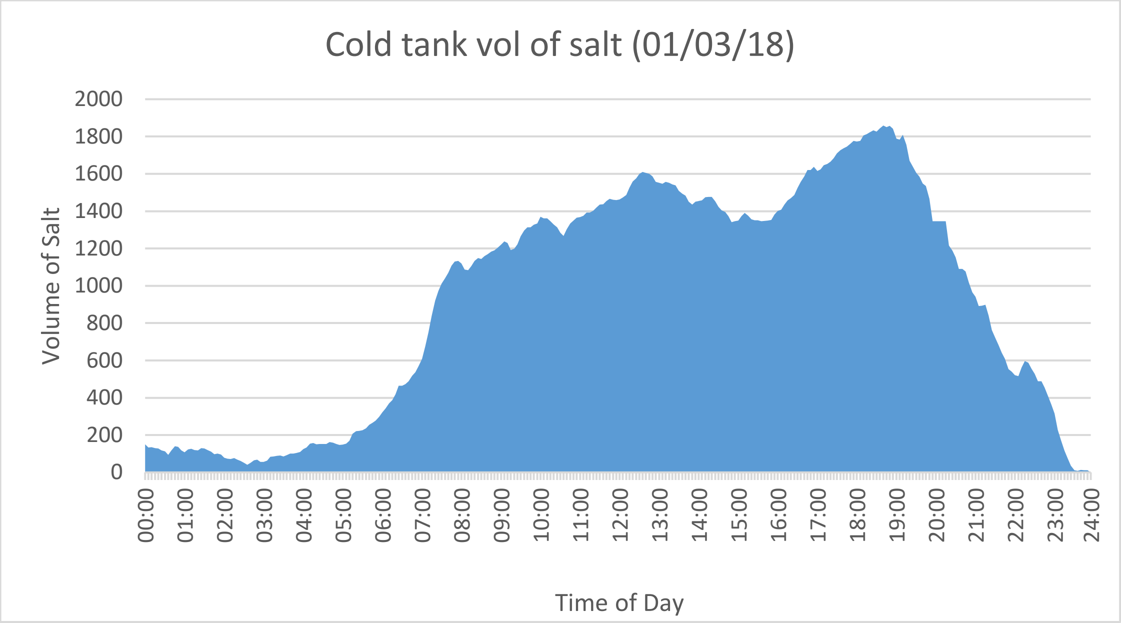


Figure 54: Volume of Salt in Cold Tank (01/03/18)

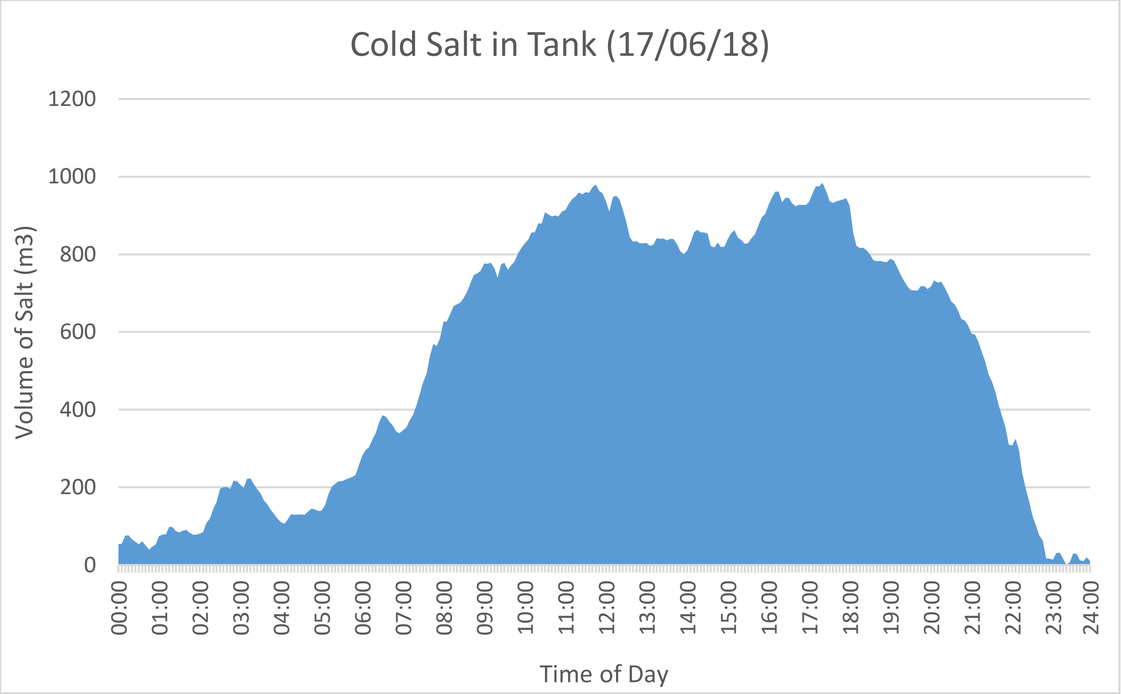


Figure 55: Volume of Salt in Cold Tank (17/06/18)

6.3) Thermal losses from tank

It was stated in by solar reserve company that they're thermal storage tanks lost 1°F a day. This value was used to calculate the thermal loss in the proposed system. The temperature difference of 1°F was converted to degrees Celsius which is approximately 0.56°C. This was the temperature change of the salt in the tank across one day. This was then converted from °C/day to °C/5 minute time interval which was found to be ~0.00194°C/5 minutes.

Thermal losses was found through the following equation:

$$Q = \dot{m} C_p dT \tag{7}$$

Where m is the average mass of salt throughout the salt within the tank per 5 minute time interval, Cp is the specific heat capacity of the salt and dT the temperature per 5 minute time interval. The winter model was used to calculate the heat loss as it had the largest average mass of salt within the tank through the 24 hour day for a more conservative value. It was found through this method that the thermal power lost through the storage tanks was 4.73MWth. This value is quite large but in terms of relativity to the thermal power generated by the reactor on the winter model which is 3151.66MWth, it can be considered almost negligible as it is 0.15% of the total reactor power originally required.

6.4) Assumptions & Justifications

- Using CCGT data for most flexible source of energy generation

Using the electrical generation data from 33 CCGT plants to model one singular nuclear-powered system that can provide the same variation in electrical power output through two separate maximum and minimum demand scenario demonstrates and validates that the UK no longer has to rely on these flexible fossil fuel powered sources.

- Thermal storage with constant flow rate

The proposed system with thermal storage was modelled to have a coolant flow rate to be as constant as this reduces the thermal power fluctuations of the reactor. This is beneficial to reactor operation as keeping the power of the reactor as constant as possible vastly reduces thermal and mechanical stresses. When thermal and mechanical stresses are reduced the life expectancy of the reactor components are vastly improved.

	Table 6			
	Time	Direct Data from 33 CCGT Plants (MWe)	Proposed System (MWe)	Fraction of Peak Power
Peak Generation Output	18:40 (March)	15820	1582	1.000
Lowest Generation Output	23:55 (March)	2690	269	0.170

As the annual minimum and maximum electrical demand profiles for the UK were used, and the salt flowrate through the reactor only varies 7.2% percentage. This is far lower than without the use of thermal storage where the reactor would have to directly vary its thermal power up to 83%.

- Parallel Connection of Turbine

Both turbines in the proposed system were modelled to be connected in a parallel arrangement to the thermal storage tank. This was done to improved thermal efficiency of the steam cycles as the heat exchangers would be both collecting heat from the salt at their highest theoretical values at 565°C. If steam generator were connected in series

- 25%-100% load range on turbines

Two turbines with 25-100% load range that were arranged in parallel connection to the thermal storage. This was done as the total plant capacity would have a lowest electrical output capacity of 12.5%; one turbine at 25% load and the other would be off. A minimum load of 25% of both turbines was chosen to minimise thermal inefficiencies, as steam turbines run at their highest efficiencies the higher the load. In reality, turbines running at 25% load would have a smaller thermal efficiency than the assumed constant value of 41%, and which also would not be constant. Two turbines were chosen for the proposed system only for demonstration purposes and to reduce complexity of the entire model for clearer understanding.

Therefore, to achieve higher overall thermal efficiencies of the plant whilst also maintaining the same overall plant efficiencies, more turbines can be installed with a smaller load range as demonstrated below in table 7 e.g.:

Table 7					
Turbine Output (fraction)	4 x 1.00	4 x 0.75	4 x 0.50	2 x 0.50 2 x 0.00	1 x 0.50 3 x 0.00
Turbine 1	400	300	200	200	200
Turbine 2	400	300	200	200	0
Turbine 3	400	300	200	0	0
Turbine 4	400	300	200	0	0
Total Turbine	1600	1200	800	400	200
Plant Capacity	1600	1600	1600	1600	1600
Capacity fraction	1.00	0.75	0.50	0.25	0.125

- Winter model salt volume for the real tank volume

The largest calculated value for the required thermal storage volume is in the winter model as it has both the highest and lowest output of electrical generation. Therefore, the summer model can still operate with these volumes as excess heat is simply stored as volume of hot 565°C salt in the hot storage tank.

- Thermal losses

Calculated thermal losses from the thermal storage system can be considered negligible as the total designed thermal reactor power of 3151.66MWth and the calculated loss was found to be 4.73MWth; 0.15% of the power generated. This is well within the power flexibility of the reactor itself as it can be powered up to 150% of its normal design load, and as low as 50%.

- Undefined MSR type

As the purpose of this report was to determine if a nuclear-powered system could be as flexible as CCGT generation, the exact type of MSR did not have to be defined as both thermal and fast MSRs can theoretically be designed and simulated to produce as much thermal energy as 3000MWth.

- Steam Generator average value

The Solar Project calculated the effectiveness of the three main individual steam generator components; the preheater, evaporator and superheater. For the proposed model's steam generator, its effectiveness was taken as the average of the three components which was 0.717 as it was assumed during operation the flowrates of the steam exiting and the water entering were equal. The preheater used in the Solar Project can also be considered negligible as the proposed system is continually extracting heat from the reactor, unlike the intermittent and nightly shutdown with the solar receiver.

- Number of heat exchangers not relevant to findings

The number of heat exchangers that were required for practical operation of the proposed system was not found as it was not relevant to key aims of the project. Generally, it was assumed that this was outside the aim as this area of engineering is more involved in detailed design of reactors/Rankine cycles. It was assumed if more heat that was required to be extracted from the reactor, which the surface area of the heat exchangers and the number of heat exchangers would simply have to increase.

- No salt plugging as experienced in the solar project

Some of the problems that arose in the solar project was that of the salt freezing during daily operation. This was caused by the requirement of salt being drained from the solar receiver at night when the sun was not available. It was assumed that this problem would be eliminated as the reactor continually produces heat, therefore, there is no requirement to drain salt line on a daily basis.

- Turbines can be powered up as quickly as needed as this already happens within the gas and coal industry

Since data was directly taken from the UK's entire fleet of CCGTs and demonstrated that power could be generated as low as 17% of the total CCGT capacity within hours it was assumed that the steam turbines used in the proposed system could be as flexible.

- Turbines can be used directly from the fossil fuel industry to cut costs

As current conventional nuclear reactors operate at ~300°C, specific steam turbines are required from turbine manufactures as the maximum temperature of steam is far lower than a coal or gas plant turbine which operates at approximately 600°C. This means that conventional nuclear plants have to purchase steam turbines that are specific to the nuclear industry. As the MSR operates at temperature significantly higher than conventional nuclear reactors at >700°C, this allows plant designs to buy turbines directly from the fossil fuel steam turbine industry.

All results, calculations and graphical data are included in attached zip file as thesis model in the appendix.

(7) CONCLUSION

7.1) Main Conclusions

Overall Flexibility

The proposed system was found to replicate a scaled-down profile of the entire fleet of the 33 CCGT gas plants that currently operate in the UK with no apparent TS sizing problems. This goes above expectations as if one plant can produce the same generation flexibility as 33 combined plants, it can be concluded that, in theory, the proposed system is more flexible than one singular CCGT plant.

TS Tank Sizing

It was expected that very large thermal storage tanks would be needed to supply the amount of thermal energy for the steam generators throughout each day. This was expected due to the dimensions of the tanks in the solar project having 11.6m by 8.4m diameter tanks and a thermal capacity of 110MWth compared to the required 3151MWth of the MSR. The cubic dimensions of the proposed systems tanks was found to be only 12.3m despite the 3041MWth difference in capacity. This was due to continual heat being generated and extracted from reactor instead of intermittent heat generated from the solar receiver.

Reactor Operation with TS

Implementing a TS system alongside the MSR allowed for a ‘buffer’ zone for a more continual heat removal from the reactor. It was found that direct thermal power that was required to be extracted between the two days throughout the year which experienced largest difference in electrical demand, that the actual power variance was 7.1%. However, it can be assumed that on a day to day basis within each month/season that the direct power variance required to be extracted from the reactor would be minimised drastically, far below 7.1%. Therefore it can be said that a combined MSR and TS system can significantly reduce thermal power variance from the reactor throughout a daily basis. This effect of vastly reducing thermal stress within the reactor increases total lifespan of the reactor and improves economics of the plant. This is a challenge that conventional nuclear plants face to this day. The molten salt TS system can only be implemented if the reactor operates at a high enough temperature to maintain salt in its molten state, which an MSR design can provide.

As the demand profiles from UK CCGT generation was taken from two days within the entire year; one with the lowest electrical demand experienced in summer and the other with the highest peak demand during winter. It was found that between these two days, even with the use of a thermal storage system, a small power variance within the reactor was still required. However, the power variance of the reactor between the day in summer and in winter, with the largest variance in thermal reactor power was found to be only 7.1%. Multiple recent MSR studies have already shown that power transients within MSR systems through simulations are easily obtained and controlled through heat extraction alone. The power of the MSR can reach thermal power transients as high as 150%, and as low as 50% of normal power. This is due to fission being controlled within the fuel salt through the process of thermal expansion of the liquid salt. To achieve the same power transients within standard PWRs, neutron absorption (boric acid) solutions and control rods have to be used which are both complex and expensive to design and implement.

Improved Safety and Associated Costs

Safety of the proposed system is drastically improved compared to PWR systems. MSR systems do not possess the same hazards and risks as conventional nuclear reactor systems due to the salt chemistry and passive safety systems. Every nuclear accident that has ever happened has occurred due to failure of supplying sufficient coolant to the reactor. This is because solid fuel cannot be transported from the reactor and remains immobile within the core. Having immobile fuel inside a reactor during an emergency situation creates vast engineering challenges as the significant amounts of heat are still generated after reactor shut down due to decay heat. For this reason, all solid fuelled reactors require backup electrical power to power coolant pumps in the event of loss of electrical power. The MSR is self-regulating, its full passive design features depend on physical phenomena and not on the function of engineered systems and components. It instead relies on convection, gravity, negative temperature coefficient and high-temperature resistance; minimising human control and interference, making the design ‘walk away safe’. No other reactor that uses solid fuel can achieve the same levels of safety and control.

The other main safety hazard with all nuclear reactors is the release of radioactive matter into the environment. This was experienced at Chernobyl and Fukushima and has devastating consequences with regards to human habitats. The main causes for radioactive release like experienced in the two nuclear disasters was caesium-137 and iodine-135, as they are both gaseous fission products that build up inside fuel pins, whilst simultaneously generating vast amounts of pressure. These two isotopes are a specific health hazard to humans as they are readily absorbed into biological tissue where they can stay and emit harmful and damaging radiation for years into cell structures like DNA. Again, this scenario of a release of gaseous radioactive matter being expelled into the atmosphere/environment is not simply not possible. All fission products, solid or gaseous, dissolve into the salt forming ion complexes, becoming trapped and immobile within the liquid fuel. Since the MSR runs at near atmospheric pressure there is also no driving force to expel the molten salt over the plant, possibly exposing employees, therefore there is no need for thick, heavy reinforced concrete containment structures currently used by PWR stations. If the reactor did experience a vessel wall rupture, the molten salt would simply seep out to be caught by a catch basin.

Final Concluding Remark

After events such as Three Mile Island, Chernobyl and Fukushima, nuclear has become far more expensive to design and construct due to regulators demand for more safety systems to be in place to prevent events like these happening again. With an MSR system, potential safety hazards already known to exist with PWR and other solid fuel systems are eliminated, therefore there is no requirement for numerous complex safety backup systems to be designed, constructed and maintained for. This vastly decreases the capital costs that are always associated with conventional solid-fuelled reactors. Using TS in combination with an MSR allows for highly flexible, and fossil-free electricity to be produced on any-scale necessary. This combined system is able to demonstrate that it is safe, cheap, fossil-free and flexible and so Government bodies and others working in the energy sector should be able to realise its importance and pursue further interest and funding into this area of work.

7.2) Further Areas of Work and Research

Replicating other Countries Sources of Energy Generation

The work of this project is confined replicating energy generation to that of the combined 33 CCGT plants within the UK. Other countries that have large deployment of fossil-fuelled plants may have vastly different electrical demand profiles than compared to the UK so could also be further investigated and analysed.

Minimising thermal stress

Although the purpose of this project was to analysis the operation characteristics of the combined MSR and TS system, minimising thermal stress through designing a model was not the main objectives, it was merely discovered by trial and error trying to reduce complexity of the model for easier analysis. The next areas of work could define their process to model a system that reduces thermal stress even further than 7.1% for optimised plant lifespan.

Salt flowrates to Steam Generator(s)

It was assumed in the model that the salt flow rates would be either evenly distributed between the two steam generators until plant capacity load went below 25% and one turbine would have to be shut down. If the combined MSR and TS system does become a reality in the future energy generation market, further investigation into optimising steam generator conditions with regards to salt flow rates must be carried out.

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(8) APPENDIX

All calculations and results for the MSR and TS model are included in the zip file as attached below: