Eng.Phys 3D03 Group 8 Final Report

IMSR (Integral Molten Salt Reactor)

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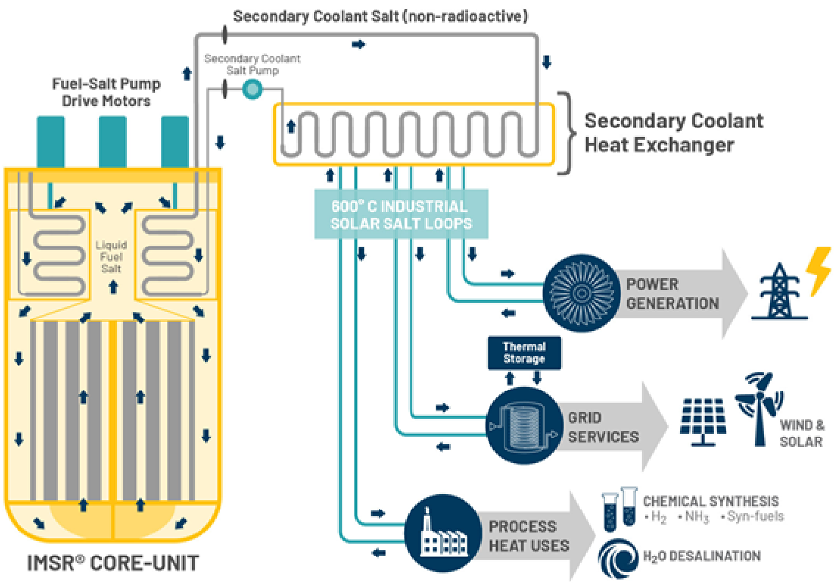
Statement

Our independent group study focuses on the feasibility of the implementation of Integral Molten Salt Reactor (IMSR) technologies in Canada. This idea was prompted by the growing interest in Small Modular Reactors (SMR) and Canada's decision to invest $20M into IMSR technologies in October 2019 [1].

Background and Purpose

IMSRs are based on the Denature Molten Salt Reactor (DMSR), a reactor designed by Oak Ridge National Laboratory (ORNL). An ISMR is a "breeder reactor" that uses a liquid fuel rather than a conventional solid fuel. This liquid serves both purposes as a fuel and a primary coolant.Since liquid salt is used CFD is utilised

IMSRs are simple reactors with few active components meaning maintenance is easier and fewer staff is necessary to operate the reactor.



The Replaceable IMSR® Core-unit

The IMSR behaves as a small modular reactor, utilising molten salt reactor technology. It's an innovative shift in a highly regulated industry that relies on outdated technology to generate its energy output. Modular reactors with their flexibility in adjusting the motherboard allows for a safe,reliable, higher efficiency, carbon free and low cost alternative to fossil fuel.

- Canada is investing $20 million in Terrestrial Energy to develop IMSRs (Oct 2020)
- IMSR use molten salts as coolant and fuel resulting in more stable thermal conditions with reduced pressure
- Uses low enriched uranium (less than 5% uranium 235U) [1]
- Graphite (moderator) limited life but replaceable
- Problem solved by using a replaceable reactor core
- Molten-fluoride-salt reactor system [2]
- Graphite's moderating efficiency is 1343 which is 2 orders greater than light water but less than heavy water at 8154 [3]
- Graphite has a lower neutron flux than light water due to the fact that the cross sectional area is smaller[4]
- Operates at 700°C with 47% thermal efficiency compared to conventional reactors that operate at 300°C with 33%. This is caused by the fact that the coolant salt has a much higher thermal stability than traditional water cooled reactor generators and phase change of salt is minimal

which reduces pressure ,that can be created by vapour, on the coolant. This ensures there are lesser limitations on final temperatures unlike water coolants.

- The difference in efficiency translates to 40% more electricity generated which increases revenue and lowers cost per unit generated.
- IMSR are smaller and use modular design; thus, easier and faster to build compared to conventional reactors. The core can become standardised therefore much cheaper and economic in comparison to custom parts. The core includes the modulator and fuel exchangers. [2]

From the above point we were able to ascertain the following advantages and disadvantages that played a factor in using molten salt reactor in our application as seen in the table below:

Advantages	Disadvantages
Safer and cheaper due to its operation at a lower temperature.This eliminates hydrogen as source of explosion risk do to the lack of requirement of large expensive containment structures	Technology is seldom used and is relatively new.
Its Modularity offers more flexibility in terms of location and replacing defective parts which is crucial in isolated regions	Its complicated design requires an extra loop heat exchanger to stop radiation from leaking as heat from the first loop.
Higher efficiency than LWRs	Lower power production
It produces low levels of fissions gases	Due to the rarity of molten salt reactor; the market lacks experienced labour for the maintenance and operation of the reactors

Analysis and Methodology

The materials of choice for the moderator is Graphite. The fluid applies lithium fluoride, sodium fluoride, beryllium fluoride , and 5% low enriched Uranium tetrafluoride fuel[5]. There have been models where the enrichment of the salt is higher through the molten salt reactor experimentation. These reactors have been deemed as potential threats therefore the enrichment is consistently low now. In the future higher enrichments could produce more energy output. Generally the IMSR is a thermal breeding reactor although there have been experimentation on fast neutron reactors with no implementation of a moderator[5]. These types of reactors produce higher efficiencies although have adverse effects on the confinement materials, thus the core will have to be replaced much more often. The salts are mixed with the fuel to increase the thermal capacities of the fuel, thus increasing the heat sink temperature [5]. All components are stored in a replaceable core unit where the material parameters follow the extreme circumstances constraints. As such, the materials are made up of a combination of alloys, carbon composites, carbides etc. that can withstand the extreme setting brought by this reactor. Haynes international is a company that provides materials that can withstand these scenarios producing materials such as Hastelloy-N which consists of Nickel and Molybdenum that both show resistive properties of thermal, corrosive and neutron flux degradation[6]. By ensuring a specific standard the materials have to withstand considering material properties, the heat sink temperatures can be increased, providing a higher efficiency.

The main model of the MSR that the IMSR has taken is classified as a Denature Molten Salt Reactor (DMSR) [5]. In comparison to LWR, the MSR can operate at much lower pressures and efficiency is not lost in coolant phase change [2]. Also the fuel is in the form of a liquid which maximizes the probability of neutron interaction and consistent chain reaction which also allows for on site refueling. Lithium-7 is generally the isotope used for the coolant salt although this can be mixed in with a Beryllium salt [7]. The reason these isotopes are used is due to the neutron cross section being very small, ensuring that the coolant does not interfere with the nuclear reaction but will still function correctly as the coolant and fuel stabilizer[7]. The Lithium-7 purity has to be very high as any Lithium-6 will produce tritium due to neutron affinity and can interfere with nuclear chain reaction and coolant loss [7]. Molten salts are known to portray corrosive features, although the IMSR has the unique feature of having a standardized replaceable core unit. Hastelloy-N is still being studied for being able to resist damage against high neutron flux. The lattice structure of graphite ensures that the neutron flux is maximized and since the melting point is very high, graphite is the most feasible moderator to produce thermal neutrons [3].

Findings and Evaluation

The IMSR is a very practical reactor model that can be implemented in the future. Since the reactor is deemed to be a DMSR, the standards ensure safe pressures [5]. The fact that it can also operate at very high temperatures ensures that the thermodynamic process to achieve energy output has a relatively high efficiency in comparison to current reactor models. The IMSR outputs 195 MW but with an efficiency of 47% this is much greater than current reactors [1]. Furthermore, the parts are standardized, it is very easy to maintain in respect to other custom reactors. Managing the reactor becomes simpler as the core unit can be easily removed and a new one reinstalled [5]. With higher energy output, this feature is very beneficial and the material parameters become constraints to consider. Since the output is less than 300 MW, it is classified as a small modular reactor and can have applications in remote areas. The reactor's fuel (potential use of thorium) and moderator(no moderator) are very adaptable as there are multiple types of reactors that can be implemented and with small changes to the model[5]. With present research, the materials can be correctly chosen to ensure the safe use of this reactor. Analysis has found that Nickel and Molybdenum, which are the main components of Hastelloy-N both, show properties that can be implemented with the MSR resisting against extreme situations [5]. The current standard practice for fission reactors are LWR but in majority of the aspects, when creating a SMR, the MSR model is much more applicable. Operating pressures, temperatures and efficiencies hold MSRs at a tier higher than LWRs. Aspects of safety and waste management are also more flexible within the MSR through its ability to implement unique models and all of these factors make the IMSR very desirable within our current society.

Stakeholders and Sustainability

The major stakeholders involved with the implementation of IMSRs are nuclear authorities such as the Candian Nuclear Safety Commision (CNSC), corporations such as Terrestrial Energies and the different levels of government. The process for decision making will include:

1. Investment into the IMSR project from the government (Canada recently invested $20M into IMSR technologies with Terrestrial Energies [1])
2. Approvals for the design and implementation of the reactor from regulatory bodies such as the CNSC
3. Implementation of the IMSR reactor by corporations such as Terrestrial Energies

IMSR technologies also have the potential for significant impact on the triple bottom line of sustainability. The integration of IMSR technologies into nuclear energies can generate economic benefits in cost savings and increased job opportunities, environmental benefits through a reduced carbon footprint and increased societal acceptance through increased safety measures.

IMSRs are able to generate economic benefits through cost savings and increased local job opportunities. The typical costs associated with shutting down a nuclear reactor for refueling are reduced with IMSRs since they can be refueled online. Additionally, the fuel form factor is a liquid which means that less costs are associated with forming the fuel into pellets. IMSRs are a category of small modular reactors and can be installed in remote locations. This in turn helps to stimulate the growth of the local economies by providing jobs for skilled labour and the energy infrastructure for local industrial development.

Being a nuclear energy source also means that the production of energy from IMSRs leaves a smaller carbon footprint than conventional fossil fuel power plants. IMSRs also have the added benefit of being more efficient (47% electrical generation efficiency) than typical first generation nuclear reactors (close to 30%) [5]. Therefore, the amount of nuclear waste produced is much lower for IMSRs. The downside to using more IMSRs is that they require very high purities of lithium-7 which is not a very abundant natural resource. The demand for lithium is growing worldwide for uses such as batteries and thus, research is being done to use Flinak and Flibe in IMSR technologies instead [8].

Countries are also more likely to accept the introduction of IMSRs into society because of their additional safety failsafes. IMSR cores run with liquid fuel that is dispersed in a molten salt. As the temperature of the salt increases the density of the fuel decreases resulting in a reduction in the reactivity of the reactor because free neutrons need to travel further to interact with atoms of the fuel. Therefore, as the temperature increases the reactivity of the IMSR decreases, adding a passive failsafe to the system. In the case that the fission reaction continues, IMSRs are fitted with drain tanks that the fuel can be emptied into to prevent the fission reaction from continuing further. The final safety benefit to IMSRs is that they operate at relatively low pressure (3 atm) compared to first generation reactors such as Light Water Reactors (150 atm) which prevents the risk of pressurized explosions during emergency situations [2].

Conclusion

ISMRs are thermally stable and safer since they operate at lower pressures [9]. The modular design of these reactors offers more flexibility when replacing defective parts; this is especially important since the molten salt used in the reactor is corrosive which decreases the lifespan of the components. They also offer a higher efficiency than light water reactors due to the high operational temperatures which could go as high as 600 °C [9] compared to 290 in some LWRs. Further, ISMRs produce manageable levels of fission gases, and these gases can be used for some medical applications [10]. The previous integral molten salt reactors have multiple advantages over LWRs; however, they also have some disadvantages such as; lower power production with an energy output of 200 MW compared to some CANDU reactors that could generate as much as 750 MW [11]. Furthermore, an ISMR requires a secondary coolant heat exchanger to reduce the effect of radiations transferred out the reactor core to the cooling cycle since the salt used in the reactor can transfer more radiation to the light water. One of the main purposes of these reactors is to be installed in remote areas as a replacement to coal and gas-powered power plants; however, because of their relatively new design; the market and industry lacks the experienced labour to maintain and operate the reactors, which makes achieving that mission more difficult.

To avoid some of the challenges that the IMSRs bring up; the industry could provide and establish a new training program in order to prepare and train new reactor operators to operate and maintain the newly built reactors especially in areas where it is difficult to find experienced labour. In addition, the industry should research the possibility of using Thorium as fuel instead of Uranium since it is safer and has a shorter half-life which makes waste management easier and cheaper. Further, researchers are still researching the possibility of increasing the operational temperature of the reactor since increasing the temperature could increase the efficiency of the reactor; thus, increasing the electricity production.

The advantages of IMSRs outweigh the disadvantages; thus, these reactors could offer a viable source of energy as countries move towards zero-carbon policies. However, these reactors are meant to be a supplement to light water reactors not a replacement.

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