ENVIRONMENTAL IMPACTS OF MOLTEN SALT REACTORS

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Nuclear power reactors have different types of radioactive waste, solid, gaseous and liquid that may impact the environment. The Molten salt reactor (MSR) is one of the most promising reactors of the IVth generation, and its environmental impact in comparison to other conventional reactors is one of its important advantages. This article will discuss and highlight the Molten-Salt Reactors, especially those utilizing thorium fuel cycle in comparison with other solid-fuel reactors.

I. INTRODUCTION

Nuclear power plants offer the best alternative to power generation and are less dangerous and impact on the environment, although these plants have different environmental impacts from nuclear fuel cycles and during their operation and from the effects of potential nuclear events. Nuclear research is still under way to reach the best nuclear reactors that reduce these harmful effects and emissions on the environment. The environmental impact of nuclear reactors can be characterized by the quantity of actinides, decay heat, and long-term radiotoxicity of the waste and the power plant emissions.

The major source of radioactivity arising from the use of nuclear reactors comes from the material classified as High-level waste HLW. HLW contains the fission products and transuranic elements generated in the reactor core. For adopted a closed cycle and reprocess used fuel, the fission products and minor actinides are separated from uranium and plutonium and treated as HLW. In reactors where used fuel is not reprocessed, the used fuel itself is considered a waste and therefore classified as HLW. HLW has both long-lived and short-lived components, depending on the length of time it will take for the radioactivity of particular radionuclides to decrease to levels that are considered non-hazardous for people and the surrounding environment [1]. The molten salt reactors (MSRs), which commonly termed by Liquid Fluoride Reactors, come in many potential forms. All involve fluorides of fissile and fertile elements mixed within carrier salts that act as both fuel and coolant to transfers fission heat from a critical core to an intermediate heat exchanger. Historically, research on thorium based nuclear reactors began after World War II at Oak Ridge National Laboratory (ORNL). The MSR designs of the 1960s and 1970s were focused on optimizing the thorium cycle to achieve a high level of breeding performance by online chemical processing. In online chemical processing system fission products are readily removed from the fuel salt by helium sparging [2]. Subsequent design studies in 1970s focusing on thermal-spectrum thorium fueled systems established reference concepts for two major design variants: a molten salt breeder reactor (MSBR) and a denatured molten salt reactor (DMSR). The primary difference between DMSR and MSBR is that the DMSR does not include an online
chemical processing plant. There has been recent research and development (R&D) activity on fast-spectrum MSRs.

Figure 1. Diagram of a molten salt reactor [3]

This article discusses and highlights the different environmental impacts of the molten-salt reactors that utilize thorium fuel cycle, in comparison with other solid-fuel reactors.

II. QUANTITY OF NUCLEAR WASTE AND ACTINIDES

The problem of nuclear waste is considered an important issue affecting the acceptability of any nuclear-related system and nuclear reactors in particular. It is very difficult to directly compare liquid fuel nuclear reactor LFNR waste production to that of traditional solid fuel nuclear reactor SFNR. But among the most attractive features of the liquid fuel thorium reactor LFTR design is its waste profile [4].

Thorium and uranium reactors produce essentially the same fission products, but they produce a quite different spectrum of actinides. According to actinide chart, the unavoidable production of Plutonium and other Minor Actinides in the Uranium cycle is a main concern for the produced radio-toxicity in the spent fuel, whereas the interesting feature of the thorium
cycle is the lower production of actinides. Figure 2 shows that five successive neutron captures are necessary to reach Neptunium, whereas the Uranium cycle is already very close to the Minor Actinides. The fraction of fuel reaching neptunium-237 ($^{237}$Np), the most likely transuranic element in LFTR, is small [5]. This leads to transuranic production 20 times smaller than LWRs, which produce 300 kg of transuranics per GWe.year.

In LWR, $^{135}$Xe, other noble gases, and fission products build up in the solid fuel arrays and the fuel pallets must be changed out before all the available uranium has undergone fission. However, in a liquid fuel, such wastes can be easily removed during operation. For example, the xenon bubbles out of the fuel as the liquid salt is circulated through the reactor core [7]. The LFTR can burn off almost all of its fuel including its own transuranic products. This means that LFTR produces almost no long term waste and very little short term waste, while achieving near total burn-up to the fuel.

In LWR, uranium fuel cycle start with 250 tons of uranium, 35 tons of enriched uranium containing 1.15 tons of useful $^{235}$U. From this, the waste produced is 35 tons of fuel containing 33.4 tons of $^{238}$U, 0.3 tons of $^{235}$U, 1 ton of fission product and 0.3 ton of plutonium [7]. By contrast, in thorium fuel cycle 1 ton of thorium is used in its entirety and comes out on the end is a ton of fission products and 0.0001 ton of plutonium which needs to be stored for a very long time. 83% of the fission products produced are stable in only 10 years and 17% in approximately 300 years [7][8]. Figure 3 below shows comparison between the amounts of raw material needed and waste production for LWR and LFTR [7].

So, nuclear waste production will be drastically reduced in the ThMSR. Total volume is expected to be 35 times less than is common in conventional reactors to produce the same amount of energy, and of what remains 99.99% is stable within 300 years, instead of the dreaded tens of thousands of years for conventional nuclear waste. In addition, ThMSRs can also burn existing nuclear waste, thus contributing to solving the existing nuclear waste problem [9].
Important reasons for the ThMSR's reduced waste profile are that it utilizes all of its fuel instead of the 3-5% common in conventional reactors, and it has a higher thermal to electrical conversion rate. Fission products that are formed can simply remain in the liquid fuel and be burned up, or removed if they are undesirable (e.g xenon gas) [4][9].

III- RADIOTOXICITY

The radiotoxicity of nuclear waste arises from the highly radioactive fission products from fission and the long-lived actinides from neutron absorption. Nuclear reactor produces two kind of radiotoxic waste – fission products such as xenon and long lived transuranic elements such as plutonium. Thorium and uranium reactors produce essentially the same fission (breakdown) products, but they produce a quite different spectrum of actinides. The various isotopes of these elements are the main contributors to the very long-term radiotoxicity of nuclear waste.

The radiotoxicity of spent uranium fuel is dominated for the first 500 years by fission products. After this period the fission products have mostly decayed and the radiotoxicity becomes dominated principally by transuranic elements, particularly plutonium [10]. The long term radiotoxicity in LWR spent fuel is dominated by transuranic elements. The following radioisotopes are classified as long term radiotoxicity of spent fuel in LWR: Selenium-79 (\(^{79}\text{Se}\)), zirconium-93 (\(^{93}\text{Zr}\)), tecnecium-99 (\(^{99}\text{Tc}\)), palladium-107 (\(^{107}\text{Pd}\)), tin-126 (\(^{126}\text{Sn}\)) and cesium-137 (\(^{137}\text{Cs}\)) [11]. The transuranic elements identified by Westlen that are major contributor to spent fuel radiotoxicity are plutonium, americium and cerium [11]. LWR has uranium fuel with content more than 95\% \(^{238}\text{U}\). These reactors normally transmute part of the \(^{238}\text{U}\) to \(^{239}\text{Pu}\) [12]. \(^{239}\text{Pu}\) with a half-life of 24,000 years, is toxic and the most common transuranic in spent nuclear fuel from the LWR [10].

LFTRs can dramatically reduce the long-term radiotoxicity of their reactor wastes. The mass number of thorium-232 is six units less than that of uranium-238, thus many more neutron captures are required to transmute thorium to the first transuranic.

All of the actinides, including americium fluorides, are highly stable in fluoride salts. The LFTR still produces radioactive fission products in it waste, but they do not last very long – the radiotoxicity of these fission products is dominated by \(^{137}\text{Cs}\) and strontium-90 (\(^{90}\text{Sr}\)). The longer half-life of the isotopes is \(^{137}\text{Cs}\), which is about 30.17 years. So, after each 30.17 years of decay the radiotoxicity reduces itself to half of its preceding value [4][12].

![Figure 4](image.png)

**Figure 4.** LFTR produces much less long-lived waste than PWRs [13],[14]

As shown in Figure 4, the relatively small amount of waste produced in LFTRs requires a few hundred years of isolated storage versus the few hundred thousand years for the waste generated by the uranium/plutonium fuel cycle. Thorium- and uranium-fueled reactors produce essentially the same fission products, whose radiotoxicity is displayed on this diagram of radiation dose versus time. Note the difference between the line of actinide waste from a light-water reactor, and the line of actinide waste from a LFTR. After ~300
years the radiotoxicity of the thorium fuel cycle waste is 10,000 times less than that of the uranium/plutonium fuel cycle waste.

The LFTR scheme can also consume fissile material extracted from LWR waste to start up thorium/uranium fuel generation. This is because the mass number of $^{232}\text{Th}$ is six (6) units less than that of $^{238}\text{U}$, thus requiring many more neutron captures to transmute thorium up to the first transuranic [7]. The radioactive fission products can similarly be removed from the reactor in days, rather than storing them for years in zirconium-cladded fuel rods of LWRs.

**IV. THE SOURCE TERM WITH FUEL PROCESSING**

The source term (types and amounts of radioactive or hazardous material released to the environment following an accident) of a molten salt reactor (MSR) with fuel processing is reduced by the ratio of processing time (time it takes to process the equivalent of a fuel inventory) to refueling time as compared to solid fuel reactors. The reduction, which can be one to two orders of magnitude, is due to removal of the long-lived fission products. The waste from MSRs (the fluid processing waste facility is nominally free of fissile fuel, which is not subject to criticality, diversion, or proliferation concerns) can be optimized with respect to its chemical composition, concentration, mixture, shape, and size. The actinides and long-lived isotopes can be separated out and returned to the reactor for transmutation. These features make MSRs more acceptable and simpler in operation and handling [15].

**V. DECAY HEAT REMOVAL**

One major safety advantage of liquid fuel is that it is significantly easier to cool down during an accident scenario, as compared to solid fuel. Solid fueled reactors must bring coolant to their fuel in an accident scenario. If either coolant or cooling power is lost, decay heat production can quickly raise the reactor core temperature to levels high enough to severely damage its structure. Unlike solid fueled reactors, the fuel in MSRs is dissolved and diluted across a substantial mass of salt, which distributes the decay heat and allows for easier cooling than is possible in an equivalently-sized solid fueled reactor. Also, liquid fueled reactors can drain fuel directly out of the core. This drainage can happen quickly, without pumping, through the use of passive safety valves and the force of gravity. One such passively safe drainage mechanism, called the freeze valve, was tested repeatedly with success during the ORNL MSRE [16] [17]. As shown, Figure 5 compares the decay heat density (MWth of decay heat per cubic meter of fuel) in a TAP reactor and an LWR over time [16].

Also, as shown in Table 1, both MSR reactors have significantly lower actinide decay heat per unit of energy than current LWRs [2], since the overall thermal efficiency of the molten salt systems is higher.

![Figure 5. Decay heat in an LWR and TAP reactor. The TAP reactor's lower decay heat density makes it easier and cool the liquid fuel during an accident [16].](image-url)
The environmental impacts were assessed based on the Environmental Impact Assessment (EIA) framework and compared to the environmental impacts of conventional nuclear power represented by the Pressurized Water Reactor (PWR), and large scale offshore wind energy as a benchmark of sustainable energy generation.

Overall the Environmental Impact Assessment indicates that the LFTR is expected to perform much better than the PWR in terms of environmental impacts. Wind power is the most sustainable option, but the LFTR leans considerably towards wind’s environmental impact profile compared to the PWR.

The performance is especially good for the “Top 4” impacts. The volume of nuclear waste produced is 35x less than in the PWR and 99.99% of the waste that is produced reaches stable natural uranium levels within 300 years. Reactor safety has improved to the point where meltdown and steam explosion can be considered irrelevant and the accidents that can occur are much less severe. The reactor has a strong inherent resistance to nuclear weapons proliferation. Although theoretically possible, it is very difficult to use a LFTR for nuclear weapons production and parties with that intention are likelier to opt for an easier path. Although it is too early to say for certain, there are indications that cost of electricity will be strongly reduced as well [18].

Because not all impacts can be considered to be of equal significance a weighting system has been applied to the simple ranking system. As the “top 4” impacts have been shown to carry the highest importance, and have a direct influence on nuclear policy and investors these were assigned the highest weights (5). The impacts of fuel cycle (3), transport (2), emission into air (4) and into soil and groundwater (2) were assigned increased weights based on their perceived importance by relevant stakeholders according to the literature [19][18] as shown in table 2.

The encouraging outcome was that the TMSR performed surprisingly well under the pressure of these strict environmental criteria. While wind power showed to be the most environmentally sustainable option as expected, with 32 environmental impact points, MSR technology leans more towards offshore wind power in the environmental impact spectrum with 73 impact points than it does towards conventional nuclear power, which was responsible for 126 points [20].

### Table 1. Summary of waste management metrics for MSRs and reference LWR system [2]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LWR (reference system)</th>
<th>MSBR (U-233 initial core)</th>
<th>MSBR (U-235 initial core)</th>
<th>DMSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinide mass per unit energy (kg/GWe-yr)</td>
<td>22,000</td>
<td>5,400</td>
<td>5,400</td>
<td>5,500</td>
</tr>
<tr>
<td>TRU mass per unit of energy (kg/GWe-yr)</td>
<td>260</td>
<td>1.7</td>
<td>1.7</td>
<td>39</td>
</tr>
<tr>
<td>Decay heat per unit energy (MW/GWe-yr)</td>
<td>Reference</td>
<td>Lower than reference (^a )</td>
<td>Lower than reference</td>
<td>Lower than reference</td>
</tr>
</tbody>
</table>

\(^a\)Qualitative comparison with reference system.

**VI. ENVIRONMENTAL IMPACT ASSESSMENT OF MSR**

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VII. CONCLUSIONS

The environmental impacts of molten salt reactors that utilize thorium fuel cycle have been evaluated in comparison with others solid fuelled reactors. The thorium fuelled MSRs are expected to produce very little nuclear waste and minor actinides, can dramatically reduce the long-term radiotoxicity of their reactor wastes, have significantly lower actinide decay heat per unit of energy and easier to remove. The free of fissile fluid processing waste can be optimized with respect to its chemical composition, concentration, mixture, shape, and size.
The reasons the TMSR has such a drastically improved waste production profile stem from its fundamentally different design.

REFERENCES

[12] Che Nor Aniza Che Zainul Bahri, Amran Ab. Majid, and Wadeeah M. Al-Areqi, "Advantages of liquid fluoride thorium reactor in comparison with light water reactor"