What happens to nuclear waste following energy production?

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Abstract

The purpose of this literature review is to analyze further uses of nuclear waste following energy production. This paper explores nuclear power as a main source of energy production that can aid in reducing CO_2 emissions in order to help combat climate change. The benefits of nuclear energy were compared against other sources, while also highlighting the remaining limitations around nuclear waste that require answers before a global shift toward nuclear energy can proceed. The categories of nuclear waste were defined prior to the discussion on the nuclear fuel cycle. The reprocessing method and vitrification processes were broken down to their components and potential for further uses, which highlighted their advantages in reducing radiotoxicity levels and volume. Lastly, deep geological repositories were outlined as the most widely accepted solution for long-term storage of high-level waste.

Introduction

With increasing pressures of the undeniable climate crisis, there is a global urgency for countries to reduce greenhouse gas emissions. Energy production alone emitted 10 billion megatons (Mt) of carbon dioxide in 2013, which accounted for 40% of the annual GHG emissions, making it the largest contributor to climate change that year. (Agustiono Kurniawan, et al., 2022). Currently, energy consumption accounts for 40% of the global energy supply. However, the growing population is on a trajectory to increase total consumption to 60% by 2030, and if we persist with our current methods of production, it is estimated that CO_2 emissions from electricity production will reach nearly 67% of total emissions (Agustiono Kurniawan, et al., 2022). Therefore, it is crucial that countries shift away from fossil fuels, instead utilizing a reliable, low emission energy source.

Behind coal and natural gas, nuclear energy is the third largest generator of electricity, providing approximately 14% of the world's total energy through 436 commercial reactors across 31 countries (Borges Silverio and de Queiroz Lama, 2011). In addition to being 36 million times more efficient at energy production compared to coal and wind, nuclear power plants emit less than 10g of CO_2 per kWh after a full energy cycle, which could offset an estimated 25 billion Mt of CO_2 in the upcoming years. (Agustiono Kurniawan, et al., 2022). Although energy production from sources such as wind turbines and solar power are socially accepted due to their decreased health risks on humans and the environment, their weather dependency makes them unreliable for consistent, large quantities of electricity. In addition, the space required to operate wind or solar can be up to 2,700 times more land than that of nuclear energy, which uses roughly 250 to 400 acres of land depending on the size of the power plant (Agustiono Kurniawan, et al., 2022).

Despite the highly desirable attributes of nuclear energy, there is still a large amount of hesitation around its expansion, predominantly from the unsolved issues around nuclear waste, including its usage and especially, the long-term storage. In order to obtain societal acceptance, assurance of safe, long-term storage of the highly radioactive material is key to ensure it doesn't pose environmental or health threats to current and future generations (Sziebig, 2021). Additionally, if there is a major global shift toward nuclear energy, it is essential that we utilize uranium to the best of our ability, with the purpose of preserving the resource for coming generations. There is high potential of using nuclear energy systems in a sustainable manner, and recycling the nuclear waste not only extends its lifeline of energy production, but also reduces the remaining level of radioactivity at the same time (Poinssot, et al., 2012)

Discussion

Categories of Nuclear Waste

Nuclear waste consists of three categories that are classified based on their level of radioactivity, which ultimately determines their required level of management for proper disposal (Borges Silverio and de Queiroz Lama, 2011). The first category is low-level wastes (LLW) which include machines and materials such as filters, papers, clothing, and tools. LLWs account for 90% of the waste volume, but only 1% of the total radioactivity (Borges Silverio and de Queiroz Lama, 2011). LLW are stored onsite until the degree of radioactive hazard is eliminated, then disposed of using common waste management methods (Sziebig, 2021). The second category is intermediate-level waste (ILW) which includes ionic resins and chemical sludge that comprises 7% of the volume and 4% of the total radioactivity. ILW requires long-term storage in stainless steel or reinforced concrete, then placed within a barrier system (Borges Silverio and de Queiroz Lama, 2011). Lastly, high-level wastes (HLW) consist of radionuclide concentrations that are long-lived and capable of producing high quantities of heat (Sziebig, 2021). For HLWs, the two management options include reprocessing or storage for future reprocessing.

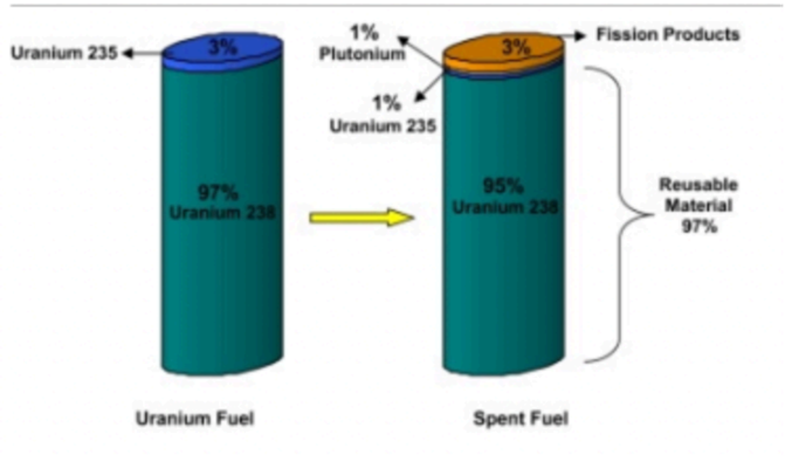

Figure 1. Nuclear Fuel Composition by L. Silvero and W. de Queiroz Lamas [Diagram] Retrieved from https://www-sciencedirect-com.ezproxy.tru.ca/science/article/pii/S0301421510007263?via%3Dihub

Nuclear Fuel Cycle

Prior to the production of nuclear waste, the nuclear fuel cycle occurs. This cycle is formed by the processes that nuclear fuel is put through before and after its use in a nuclear power plant to produce electricity. Thus, two main nuclear fuel cycles can be distinguished. The front end, which occurs after the arrival of the nuclear fuel at the nuclear power plant, and the back end, which occurs after the spent nuclear fuel leaves the reactor (Rodriguez-Penalonga & Moratilla, 2017). The process to which spent nuclear fuel goes under, varies according to the cycle strategy used. Two cycle strategies are implemented nowadays, the once-through cycle and the twice-through cycle. The front end is similar for both cycles, since uranium mining and fuel fabrication happens in both types of cycles. However, the back end is where things differ between the cycles.

On one hand, the once-through cycle considers spent nuclear fuel to be high-level waste and consequently, it must be disposed of in a storage facility for millions of years, until its radiotoxicity reaches natural uranium levels (Rodriguez-Penalonga & Moratilla, 2017). On the other hand, the twice-through cycle considers spent nuclear fuel to be an energy source due to its composition of approximately 96-97% recyclable materials, 94–96% of which is uranium (1% approx. of U-235) and 1–1.5% is plutonium (Rodriguez-Penalonga & Moratilla, 2017). Thus, to exploit the potential of the spent nuclear fuel in the twice-through cycle strategy, the fuel must be reprocessed to extract the uranium and plutonium, which can be recycled to make fresh nuclear fuel. This fresh nuclear fuel can be used once again for more energy production.

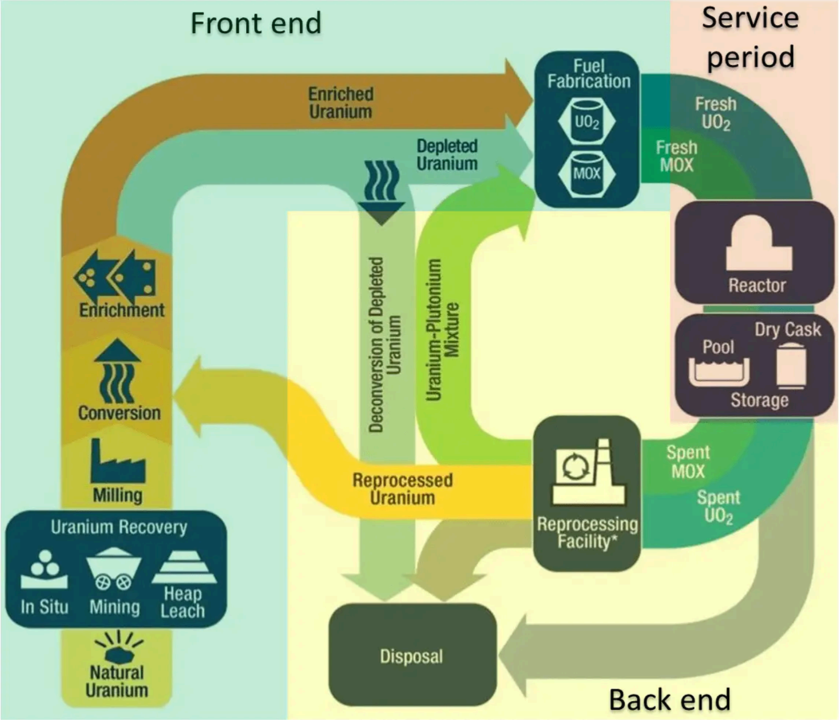

Figure 2. Front and Back End in the Nuclear Fuel Cycle. From Twice-through Fuel Cycle, by Nuclear-Power.com, 2024, https://www.nuclear-power.com/nuclear-power-plant/nuclear-fuel/nuclear-fuel-cycle/twice-through-fuel-cycle/ Copyright 2024 by Nuclear-Power.

Mixed Oxide of Uranium and Plutonium (MOX) Fuel

This material produced from potential fuel still existing in the twice-through cycle is called MOX (Borges & Lamas, 2010). The reprocessed MOX fuel has several advantages over fuel that would be directly stored as high level waste. Reprocessed fuel reduces the long term radiotoxicity of the waste, which ends up minimizing public concern for the storage of nuclear waste. Long term heat production is also reduced, which increases the capacity of storage of waste (Borges & Lamas, 2010). Additionally, the volume of high level waste is reduced, which leads to less space being required for the inevitable storage that comes with nuclear energy production.

MOX fuel is achieved through the plutonium-uranium extraction method (PUREX). In the PUREX process, spent fuel is cut into small pieces which are dissolved in nitric acid and the solvent extracted using tributyl phosphate. Uranium and plutonium are separated in multiple extraction cycles and purified with a 99.9% efficiency (Borges & Lamas, 2010). The rest of the liquid, which contains fission products and minor actinides is processed and glazed, and then is encapsulated in a steel container, where it is finally stored with the rest of the high level waste. The PUREX process is already widely used in certain countries like France, Japan, India, Russia and the United Kingdom (Borges & Lamas, 2010). Meanwhile, the United States has no current reprocessing plants in operation, nonetheless, it is one of the countries that could benefit the most from nuclear reprocessing. The potential fuel available for reprocessing kept in repositories could supply all of the reactors in the United States, producing 100 Gigawatts (One billion watts of electric capacity) for 30 years, without the use of new uranium (Borges & Lamas, 2010).

CO_2 Emissions

Regardless of whether the waste is reprocessed or not, it is important to remember that reprocessed waste and non-reprocessable waste still need to be disposed of and stored in the long-term, so starting reprocessing would not replace repositories of waste (Saidi & Omri, 2020). Despite this, reprocessing spent nuclear fuel in countries like the US should be a priority, since this can reduce the volume of high level waste that is stored in their repositories. More importantly, it allows for an increase of energy supply, but also to reduce CO_2 emissions. This is thanks to the fact that nuclear energy plants emit a negligible amount of CO_2, along with hydroelectricity and wind power. Nuclear power emits less than 15 g of CO_2 equivalent per kilowatt-hour, while coal energy emits around 740 g of CO_2 equivalent per kilowatt-hour (Saidi & Omri, 2020). Thus, nuclear energy can help solve energy supply problems while also having environmental benefits, which are not climate dependent.

Vitrification

Regarding the high-level waste, as previously stated, all spent nuclear fuel, reprocessed or not, has to be eventually stored for the long-term until its radiotoxicity reaches natural levels. This high-level waste is a liquid stored in underground steel tanks. However, this is not the end for the waste, since one more process can be applied before storing it definitely: vitrification. Vitrification is a process by which high level waste is solidified and turned into glass, in preparation for disposal in a geologic repository (U.S. NWTRB, 2017). Vitrification can be used for large volumes of high level waste, and the resulting glass product is chemically durable in many geologic disposal environments. More importantly, this process further minimizes the volume of the waste, making it occupy less space (U.S. NWTRB, 2017).

Long-term Storage

While the highly debated question of optimal long-term storage for HLWs has been researched for decades, it continues to persist due to the lingering fears of radioactivity and the extensive lifetime of the waste, which is far beyond human history (Poinssot, et al., 2012) The most widely accepted solution for final disposal is deep geological repositories (DGR), which consist of a series of engineered barriers, including metallic containers and clay buffers that work together to isolate the waste from humans and the environment, whilst being stored approximately 500m underground (Agustiono Kurniawan, et al., 2022). Though this may seem like a simple solution, appropriate locations to build the repositories are a rare resource due to their strict requirements of geological suitability, low risk of natural disasters and acceptance by local populations (Poinssot, et al., 2012). This means that DGRs must be managed to their highest efficiency to accommodate HLWs for as long as possible. Presently, Finland is the only country that has taken the steps towards creating a DGR, with their facility ‘Onkalo’ being the world’s first long-term nuclear waste storage facility. At 420m below ground, Onkalo was designed to store HLW for 100,000 years, using crystalline bedrock and copper canisters for barriers to protect against water access and prevent radionuclide leakage (Agustiono Kurniawan, et al., 2022). Although DGRs are the most viable solution for long-term storage, the timespan required to build one is considerably long, which highlights the level of importance in management techniques and ensuring proper knowledge transfer between generations to allow DGR projects to continue (Poinssot, et al., 2012).

Conclusion

It is imminent that nuclear power is vital for reducing greenhouse gas emissions, while simultaneously providing reliable, low carbon energy. Even though the production of nuclear waste is unavoidable, spent fuel must be viewed as a resource, as the reprocessing of spent nuclear fuel allows for humanity to get more energy out of nuclear fuel before its final disposal. This is also important in order to sustainably preserve the resource for future generations. Reprocessing, along with vitrification can greatly reduce the volume that high level waste occupies, as well as reducing the long-term radiotoxicity, which inturn, extends the usage of deep geological repositories. DGRs are an achievable, long-lasting and sustainable solution, that provide public safety and prevent environmental harm.

Recommendations

Global collaboration between countries should be sought to accelerate advancements in technologies and increase spread of knowledge and understanding behind safety, in order to gain societal acceptance. Additionally, further research must be dedicated to the recycling of MOX fuel, allowing for more energy to be produced before the inevitable final disposal of the nuclear waste; henceforth, creating a greener world whilst maintaining energy demands.

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