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The benefits of incorporating nanomaterials in nuclear power

Chengxiu Li

Kristin School, Auckland, 0632, New Zealand

44103@kristin.school.nz

Abstract. Nuclear power has been a prominently considered power source for decades. Potentially being the most efficient fuel source surpassing hydro-electric, coal, and wind. The splitting of atoms and the chain reaction that results can release tremendous amounts of energy from very little fuel. However, it is also very controversial which accidents such as chornobyl and extremely long-lasting waste products. But with the incorporation of nanotechnologies such as nano-crystallized uranium oxide as fuel, and oxide dispersion-strengthened (ODS) alloys as a way to strengthen reactor hardware even under high temperatures. Nuclear energy could be made much safer, and even introduce commercialized fusion power with efficient deuterium extraction from seawater, and copper carbon nano alloys to act as an efficient heat conductor. Nuclear energy in the production of power has a huge future potential and could make its way into many more applications such as space exploration, shipping, and more. Nanomaterials used could help speed up the process, making it efficient, smaller, and safer.

Keywords: nanomaterials, nuclear fission, nuclear fusion.

1. Introduction

Nuclear power is the manipulation of matter on the atomic level to produce energy. The mechanics of how the energy is used to generate electricity is generally the same as other sources, using converting the heat generated by the reactor into kinetic energy through boiling water, then the resulting steam driving a large turbine to produce energy for homes and cities. Nuclear power is one of the relatively clean sources of energy, producing no carbon emission since no chemical burning is involved, and producing little to no waste. Its two main branches, fission and fusion also generate much more energy that is more likely to meet modern-day's high energy demands than other completely clean sources such as solar and wind which can be unreliable with different physical conditions.

Nuclear fission has increasingly become mainstream in energy production today. From the first reactor in 1942, it has gained favour in the 1950s and 1960s, as a reliable way to generate large amounts of electricity from very little fuel [1]. However public perception slowly decreased the attitude toward nuclear reactors. The fear of radiation and contamination is partly amplified by the relatively new discovery of its harmful effects. People feared a "radioactive apocalypse" caused by the use of nuclear fission reactors. This fear was further amplified by nuclear accidents that gained significant news headlines such as the: 1961 SL-1 nuclear meltdown; 1979 Three Mile Island accident; 1986 Chernobyl disaster; 2011 Fukushima Daiichi nuclear disaster [2].

These accidents spread widespread fear across public perception, forcing governments to cut down the construction of nuclear power plants. This was detrimental for many reasons. The first is that nuclear

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power actually has caused significantly fewer casualties and deaths than other power sources. Coal plant fires and hydroelectric dam failures have all individually caused significantly more damage in both properties and lives than nuclear power. In fact, the death rate per terawatt hour of brown coal is almost 2000 times that of nuclear power. At 0.04 deaths per terawatt hour compared to 57.34 per terawatt hour. This is also due to the large amounts of polluting chemicals released into the air from chemical combustion that causes lethal cancer and diseases. The process of nuclear fission is perhaps one of the most environmentally friendly methods of producing enough power to sustain a large population. The process of nuclear fission is when a heavy element such as uranium is struck by a neutron in which it "splits" into lighter elements and 2 neutrons which then repeats the process forming a chain reaction. The process is much more efficient than chemical combustion, releasing much more energy for fewer materials. Moreover, it only produces small amounts of nuclear waste, and no carbon emissions. However, even with modern cautions and strategies under use, the number of nuclear accidents has not decreased by number. This is why nanomaterials such as ODS alloys need to be implemented in order to make nuclear energy safer and more sustainable.

Nuclear fusion is the process of fusing atomic nuclei of lighter elements into heavier elements, releasing relatively large amounts of energy. Due to this, progress and effort have been carried out to make controlled artificial nuclear fusion inside a reactor, to commercialise using nuclear fusion as a readily available energy source. The use of nuclear fusion is advantageous over traditional energy sources and nuclear fission for multiple reasons. For example, nuclear fusion produces no carbon emissions. Its only waste product is helium, an inert unreactive gas that is actually prized to be used in other products and applications. However, it comes with many challenges. Sustained fusion is hard to achieve due to factors such as difficulty in igniting fuels, precise engineering, and materials being unable to withstand intense radiation. Recent studies, however, have shown that nanomaterials could be used to solve these problems. For example, nanomaterial fuel capsules could reduce the energy needed to start the chain reaction. Fusion pellets containing reactant isotopes can be nanotechnology engineered to be easier to combust and to be combusted more controllably.

Materials can also be enhanced by using nanomaterials to withstand much higher temperatures and pressures, having much more tensile and ductile strength, which could help reactors better withstand the high temperatures of nuclear fusion, ensuring the reaction continues in a contained manner. Nanomaterials can also be used to increase the precision of control of fusion plasmas in tokamak magnetic confinement reactors.

2. Nanomaterials in nuclear fission

2.1. Nanomaterial in nuclear fission fuel

Nanotechnology can be incorporated into nuclear fission technology to create and produce more efficient and precise fuel.

The use of uranium is the most common form of nuclear fuel in fission. However, out of the many isotopes of uranium, only uranium-235 is fissile material. The uranium composition available on the earth is as follows (Figure 1).

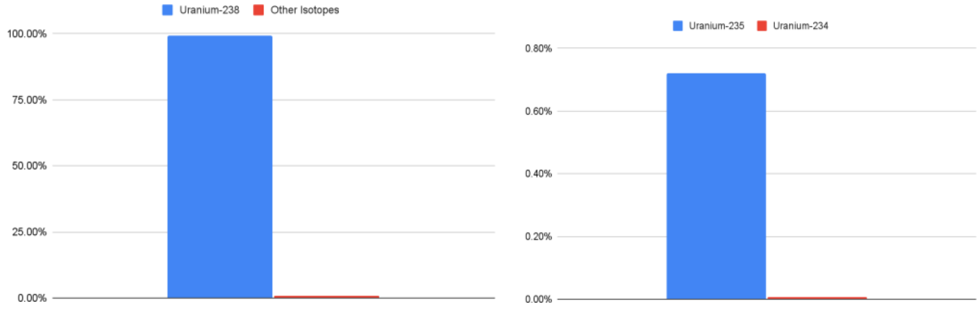

Figure 1. The uranium composition available on the earth.

The majority of naturally occurring uranium is in the form of U-238 which is not fissile material and does not participate in fission chain reactions. Due to this, Uranium-235 needs to be refined through lengthy and expensive processes to purify it from 0.7% to 3.5% which is what is commonly used in Light Water Reactors (LWR) [3]. this process includes expensive equipment such as centrifuges, making extracting usable uranium expensive, up valuing reactor-grade uranium.

This makes the need of getting as much out of fuel as possible a major concern. 1 gram of uranium-235 releases around 10^{11} joules, making one gram of reactor-grade fuel containing about a similar amount due to uranium’s high atomic weight [4].

The first way to improve this is through incorporating nanostructures and technology within the fuel itself. H. Wu et al. found the effectiveness of using Uranium Dioxide nanocrystals particularly interesting [5]. The study created these nanocrystals through thermal decomposition by organic acids such as oleic acid then precipitated through the use of further organic compounds such as hexane and acetone and found regularly spaced micro-structured pores which pose many uses. The size of these pores could even be easily customised by altering the properties of organic compounds used such as the length of hydrocarbon tails. They found that during a reaction, highly reactive fissile substances produced by uranium fission such as iodine could fill these pores and prevent it from reacting with other fissile materials to reduce unwanted chemical reactions and the formation of fuel clads. Moreover, the study also showed that uranium nanocrystals have improved radiation and thermal stability, due to their chemically unreactive nature, improving their safety and burnup rate. The manufacture of these Uranium oxide nanocrystals is also relatively stable and reliable the yield resulting from this reaction being 78% nanocrystal synthesis, allowing for an efficient and massive result from its manufacturing [5]. The results from the multiple experiments conducted also showed the production reliability of the nanocrystals from the production. Properties of the UO_2 nanocrystals that were produced with the same intent such as crystal size in nanometres, distribution, and pore size remained consistent, with changes in size and structure being only under 3% across all experiments. Overall, the quality and physical properties of Uranium Nanoparticles as a fuel source is shown to be reliable and easier to produce and use.

The second way to improve this is to enhance the capture and synthesis of uranium through the use of nanoparticles as part of the purification. The majority of uranium mining for nuclear fission plants is from underground. This process is tedious and requires the drilling of tons of rocks for uranium ore, which then needs to be purified through a long process requiring it to be crushed and ground into a powder, then through chemical processes, resulting in uranium fluoride (UF_6), which then after heating produces Uranium Oxide (UO_2) which can finally be used in nuclear fission [6]. This process is lengthy and has several hazards along its production. As the demand for nuclear energy increases, the current reserves for uranium will deplete, raising the cost of nuclear power. The distribution of uranium is also not even. U_3O_8 is the world's most economically extractable uranium ore. Australia and Kazakhstan have over 33% of all extractable uranium globally, and only 15 other countries have enough to sustain ore to sustain nuclear power [7]. At the rate of current consumption, uranium reserves will run out in ~80 to 100 years. the availability of uranium needs to be increased for nuclear power to become mainstream.

One solution to this uranium shortage problem is to extract uranium from seawater. when many nations realised the potential of nuclear fission energy, the first study was conducted in 1953 by the UK [8]. According to some studies, the amount of uranium in the ocean could reach 1000× the amount of terrestrial uranium ore making it essentially inexhaustible. Its concentration is low at 1.4×10^{-8} mol/L, but it is mostly in the form of $UO_2(CO_3)_3$ which is very easy to purify into Uranium Dioxide and due to the high efficiency of uranium, an unreachable amount is not needed to be extracted quickly in order to match consumption [9]. However multiple challenges come with extracting uranium from seawater. The concentration as mentioned above is very low, so the extraction process must be very efficient. The concentration and type of elements also vary with different flows and sections of the oceans. Ions such as alkali metals, rare earth metals, and halogens can all affect the chemical process and compete with uranium [7].

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Nanoparticles, however, can be used to improve these results and help mitigate some of the problems through better chemical properties or avoiding conventional chemical purification entirely.

The first potential nanoparticles to be used may be Magnetic Nanoparticles (MNPs). Their unique size and shapes have unique properties such as high magnetic susceptibility and low curie point. For example, one particular study showed the potential of goethite in the extraction of uranium oxide or uranyl ions. Geothite or α-FeOOH nanocrystals have been shown to aid the extraction of uranium from aqueous solutions. Under natural pH levels of 7.3, the nanocrystals performed well and allowed for a significant increase in absorption and extraction of U (VI) from aqueous solutions, giving a substantially increased yield. This was clear in one of the experiments included, the reaction finished in only 130 minutes when the equilibrium was reached through the use of concentrated Goethite nanocrystals [10]. The nanocrystals were shown to be unstable when exposed to large amounts of competing ions, but that would not be present in seawater, only in mines.

Another potential use for nanoparticles would be for Iron (III) Oxide coated with acids. This coating can help with the sorption and binding capacity of Uranium ions, and greatly increase the yield from passing seawater through uranium refineries. One specific review showed the effects of different amounts of Humic Acid (HA) coatings on this MNP iron (III) Oxide on the effect of uranium yield and sorption.

The study first showed the ease of manufacturing said Acid coated Magnetic Nanoparticles and the potential for commercial production [11]. Aqeuos Iron Chloride and Aqeuos Iron Sulfate were added to excess water, which is then exposed to ammonia then heated up then cooled to 23 ºC, maximizing the yield of the MNPs. The products would be easily recovered through the use of a powerful magnet. Then the Iron (III) oxide will be combined with variables mount of humic acid to get desired sorption effects, and again retrieved through the use of a magnet.

This method was relatively simple and easy on paper and would be simple to implement on a large-scale production line, due to the relatively few ingredients and straightforward heating and cooling, requiring no specialised infrastructure. The study then used the method that created the Iron Oxide MNPs with variable amounts of Humic Acid coating. It concluded that all MNPs with Humic acid coating had some effect on improving the sorption rates of Uranium from aqueous solution, including seawater which has been removed from organic products. The large Effect was on 20 ppm-20 ppb concentrations of uranium. The study concluded that the maximum sorption capacity of these materials was finalised and found to be 5.5, 10.5, 18 and 39.4 mg of U/g of NPs for Fe_3O_4, Fe_3O_4/HA 1, Fe_3O_4/HA 2 and Fe_3O_4/HA 3 NPs respectively. This proved the increased capacity of MNPs which had been coated with HA [12]. This study proved the ability of MNPs to be modified and how that could potentially affect the efficiency of extraction of uranium from various scenarios.

In conclusion, the use of nanomaterials in the production and encasing of nuclear fuel is greatly beneficial to the safety and efficiency of fission reactors. The future incorporation of these into fission may help extend the lifetime of fission reactors, and make it a more sustainable source of energy.

2.2. Nanomaterials in nuclear fission reactor materials

Using Nanomaterials in nuclear reactor hardware is a good way to improve the efficiency and reliability of the reactor. Nanomaterials or structures in vital components such as control rods and fuel cells could greatly reduce accidents and improve the overall safety of fission reactors.

This is very prominent in the enhancement of Alloys through nanoparticles. Alloys and materials needed for reactor materials need to be incredibly heat and pressure resistant due to the large amount of radiation and pressure from heated steam that powers dynamo generators. They also need to be ideally radiation resistant and radiation blocking to prevent alpha, beta, and gamma radiation from polluting the surrounding and becoming a hazard to workers. This is especially needed in the casings, pipes, fuel-containing modules, and control rods.

The containment buildings and walls are nuclear reactors are usually made of Steel, or Steel reinforced concrete [13]. And the pipes and internal workings can be made of highly flexible steel and nickel alloys [14].

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However, these conventional unmodified materials have disadvantages. Steel and reinforced concrete are rather heavy and structures require extensive supports that can become expensive. Highly flexible steel and nickel, although not brittle can bend and deform much easier. This made for the innovation in high-strength alloys that results in ODS alloys, or Oxide Dispersion Strengthened alloys are alloys that are enhanced with oxide nanoparticles, such as ceramic. They have much-improved strength and do not contract or expand under temperature differences and stress. They also demonstrate corrosion resistance and high strength even at extreme temperatures.

This is proven by a study that aimed to look at the properties of ODS Alloys At very high temperatures. A sample of 12YWT ODS alloy and V_4Cr_4Ti was put under 800 ºC heat environments. The ODS alloy showed significant strength over the conventional material, lasting for over 14500 hours when compared to V_4Cr_3Ti which failed after 4029 hours. Not only that, but the ODS alloy also had more stress applied, at 139 Mpa compared to 77 Mpa applied to V_4Cr_3Ti. The ODS alloy also had much smaller deformation at only 2.3% elongation, while conventional had over 52% elongation [15]. This experiment showed the heavy improvement ODS has over normal alloys, proving their strength while under the high temperatures of a nuclear core, and having minimal deformation and stretch to keep pipes and rods in shape.

3. Nanomaterials in future uses and nuclear fusion

3.1. Nanomaterials in fusion fuel

The most likely future source of fusion would be in the form of deuterium tritium (DT) fusion and deuterium deuterium (DD) fusion. This form of fusion produces the most energy at the lowest temperatures making it much more feasible than other methods.

Both of these fusion reactions require deuterium, which is an isotope of hydrogen with 1 neutron, making it significantly heavier, henceforth the name “heavy water”. The currently most economical method of deuterium production is the separation of deuterium from natural water sources such as seawater. The estimated concentration of deuterium to hydrogen ratio is 1-5000 [16]. This ratio is much lower than uranium-235 to uranium-238, but due to water being both a lot more common and concentrated, the overall access to deuterium is much easier than uranium, which has to be extracted from deep mines or sparsely from seawater. Since it is an isotope of hydrogen, it is chemically identical. Therefore, the extraction process is usually long and complicated. The main method is the electrolysis of seawater in which water is passed through with a current, causing the oxygen and hydrogen isotopes to split, with fewer parts of the hydrogen gas being deuterium. The hydrogen is then separated or repeated until deuterium oxide is in nearly pure form, separated from the hydrogen and can be used for DD or DT fusion.

This process requires lots of energy for the electrolysis and distillation making it less efficient. However, through the use of nanomaterials, there are ways to make this process more efficient or even to avoid it. One example would be membrane separation. The traditional method of electrolysis is inefficient and power-hungry, and lots of nuclear isotopes are wasted as a result of its non-exact nature. The membrane distillation process is a far better option. In membrane distillation gas is passed through layers of membranes which slowly filter out the desired isotope, due to the differences in mass and volatility [17].

Different nanomaterials have been used to improve the durability of membranes. For example, Wen Ming et al. conducted a study that showed that special F-graphene oxide (GO) nanomaterials enhanced membranes could maintain their coating for over 90 hours under heavy usage. However, it is to be noted that the main advantage of this method is that a lot less deuterium is lost in the refining process.

The storage of deuterium and other isotopes of hydrogen can also be tricky. Because of their small size, they can escape containers easily even with the smallest of gaps and porous structures. Carbon nanotubes (CNTs) can help with this situation with multi-walled CNTs being able to hold up 4.6 wt.%. Boron nitride nanomaterials also have similar storage capacity, but are also heat resistant and electrically insulated. Even better examples include magnum alloy hydrides which can hold around 7 wt.%

3.2. Nanomaterials in reactor materials

Materials for fusion reactors must be very strong, heat resistant, resistant to corrosion and oxidation, and provides radiation resistance and protection.

Although conventional carbon materials were used due to their organic nature and high melting point, a downside to it is its low heat conduction at high temperatures that would occur inside a reactor. The solution to this would be to blend carbon and metals to form a composite nanomaterial that is both radiation resistant and have high thermal conductivity. Copper-Carbon composite nanomaterials have been shown to have enough thermal conductivity up to 1130 ºC [18]. Other studies also investigate the incorporation of molten copper and copper titanium oxide into carbon nanocrystal structures can improve both heat transfer and structural strength.

4. Conclusion

This paper introduces the potential for nanomaterials to benefit both nuclear fission and fusion power, and its potential to negate some of their problems. This paper reviews several academic journals and studies. Concluding from the studies provided, there are some areas clearly in need of further development. for example, the monetary and energy cost of extracting significant amounts of fissile material from seawater is a large hurdle to overcome, if that method were to ever become mainstream. however, the positives of incorporating nanomaterials can be said to overweigh the potential challenges. nanomaterials can be used to positively affect the efficiency and availability of nuclear power around the world. For example, the use of MNPs to efficiently extract uranium from seawater is possible and could make it widely available across the world. Incorporating nanostructures into nuclear fuel itself can help reduce the build-up of reactive or corrosive byproducts and improve the overall safety of nuclear fission. All of this allows nuclear fission to be a viable intermediary source of energy to transfer from fossil fuels to cleaner sources such as fusion. Nanomaterials can also help make nuclear fusion more feasible and cheaper once commercialised. Containing and extracting fusion fuel can be made easier through the use of nanomaterials, and the materials required to maintain the high pressure and temperature of the reactions can also be made available. Overall, the use of nanomaterials can greatly benefit the nuclear industry and help make it a more widely used energy source.

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