Nuclear Power

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Abstract

Since Fermi's discovery of the concept of nuclear fission in 1934, the world has developed it for a source of power and weaponry. Nuclear technology is the energy released by splitting the atoms of specific elements, which results in a large amount of power by a relatively small fuel source. Nuclear fission can provide energy for cities, or condensed into a catastrophic weapon. Unlike its rivals for energy production such as coal and natural gas, nuclear plants do not release greenhouse gases into the earth's atmosphere. However, it produces a significant amount of radioactive waste that needs to be properly disposed and stored. This paper outlines the function and issues with current technology like the common LWR plant, as well as the failings and disasters in our history. It then highlights the future technology and improved systems such as MSRs, SMRs, and the WAMSR. A glossary of terms and a bibliography of sources are provided after the essay.

Introduction

Nuclear power holds vast opportunity. It has become one of the most common ways of generating electricity as is recognized as being the largest clean energy source. However, with climate change becoming more of an issue, it is time to reevaluate safety and policy surrounding nuclear power and what it can be utilized for to better our current situation. The purpose of this paper is to inform on the benefits and issues surrounding nuclear energy.

History of Nuclear Power

In 1934 Physicist Fermi tested uranium by bombarding it with neutrons and found that the reaction obtained was much lighter than the element, he discovered the potential of nuclear fission. This led to him creating the first self-sustained nuclear reaction (HISTORY). This was done by utilizing uranium and control rods, similar to how we do it today. Seeing as this harnessed great potential, the United States carried out the first tests pertaining the nuclear bomb, the location was the New Mexico desert in the year 1945.

Figure 1: A photo of the nuclear reactor in Pennsylvania

This sprouted a new age for nuclear power plants (1950-1960). At the time they were classified as safe, and as great alternatives to the energy practices present at that time. The amount of energy that can be harnessed/produced by fission of a uranium atom is about 10 million times the energy that of a coal molecule. In simple terms, the uses of uranium atoms are vast and growing.

For a nuclear plant to run, the uranium utilized must be overheated, this will help it be close to meltdown temperature. In order to prevent nuclear meltdown, the nuclear power plants must be in constant watch and have a series of fail safes to protect the people in nearby areas from radiation poisoning. This danger was only made aware and known to the public in 1979 after the incident of the nuclear reactor in Pennsylvania overheating (U.S.NCR, 2014). No one was injured but it did open and call attention to the dangers surrounding nuclear power.

The discussion of whether or not the risk should call to end nuclear power is divided. Nuclear power is complex and it calls for constant monitoring. The fuel rods in such plants must be changed every 2 years due to the uranium inside becoming spent and because of the damage the rods will sustain if not dealt with accordingly (Sidorov, Vasiliev, 2012). Uranium is very delicate when dealing with. It creates and releases a lot of heat and radioactivity, meaning that the rods it is located in, must be dealt with carefully so it does not harm the surrounding.

The half-life of uranium is long and the rods replaced every two years will be radioactive for hundreds of thousands of years to come (refer to figure 2). Meaning that the locations/storages they find themselves in right now, will eventually need to change or expand. There are various approaches to deal with this, such as many European countries implement reprocessing plants, by doing so they remove the leftover uranium from the rods when cooled sufficiently. An interesting use for some of the products of reprocessing is that it can be implemented to energy purposes.

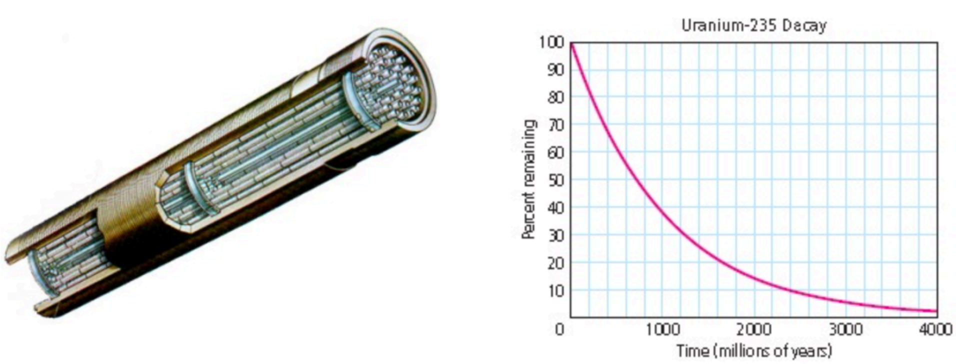

Figure 2

In the late 1970's, the current president at the time, Jimmy Carter, promised to bring an end to nuclear weapons such like President Nixon, who began the close of US reprocessing plants in 1970. It was assumed that if the US took initiative to end the program, other countries would follow suit. This has not been the case, many countries have continued if not evolved their use of nuclear power and implementation of plants. It has been pointed that the policy implemented by the US does not stop countries like North Korea and Iran to find and put to use uranium. It is a heavy topic of discussion that continues today.

Issues

It is difficult to separate the concepts of nuclear warfare and nuclear energy. Nuclear bombs create a chain reaction that accelerates exponentially. Reactors are designed to prevent this chain reaction from occurring. The concentration of fissile material is too low in reactors, so it does not allow for that explosive chain reaction to happen. Reactors in plants contain materials that absorb excess neutrons. While the production of energy is not the same as being weaponized, it does not mean it is not dangerous. After undergoing fission, plants need to dispose of decay heat, which derives from radioactive decay. There is a need for operator intervention and constant cooling to actively prevent issues, and if this ever fails, it can be catastrophic. There have been three notable disasters involved with failure to cool a nuclear reactor; Three Mile Island, Chernobyl, and Fukushima Daiichi.

The Chernobyl accident happened during a test to see how the plant would operate if it lost power. Despite existing design flaws and accidents, they proceeded with shutting down safety systems that would be lost during a power outage, including the turbine system that provided cooling water. With the flow reduced, the cooling water in the reactor began to boil and turn to steam. Operators tried to reinsert rods to slow and control the nuclear reaction, but a design flaw in the control rods caused them to jam. The steam likely caused an explosion in the reactor and caused another explosion seconds later (April 26). The area of this disaster is 400 times the size of the area of Hiroshima, and the immediate area of Chernobyl will not be habitable for humans for 20,000 years (Lallanilla).

The disaster of Fukushima in the year 2011 could not have been prevented, because it was caused by the largest earthquake ever recorded in Japan. The nearby earthquake was measured at a 9.0 on the Richter scale, causing a 15 meter tsunami to disable the power supply of the plant. The waves of the tsunami submerged and damaged the seawater pumps for both the main condenser circuits and the auxiliary cooling circuits, notably the Residual Heat Removal (RHR) cooling system. They also drowned the diesel generators and inundated the electrical switchgear and batteries, all located in the basements of the turbine buildings. About one hour after shutdown of the fission reactions, the reactor cores would still be producing about 1.5% of their normal thermal power, from fission decay heat, measuring at about 55 Megawatts. No deaths were caused by the radiation or failure of this plant, but lives were lost due to the initial natural disaster (Fukushima).

These catastrophic events need to be measured against the need for power supply, as well as any alternatives that will also have costs and risk. In the year 2009, the combined electrical power of the world's commercial reactors of 370 Gigawatts, or 2,600 kWh, provided 15% of the world's energy consumption. If all of these reactors were replaced with coal plants, the amount of greenhouse gases released into the air would be an estimated 4,000 million metric tons. This would be on top of their existing output, as 41% of the world’s energy was produced by coal in the same year. If the same amount of energy production of nuclear plants were replaced with natural gas plants, 2,000 million metric tons of greenhouse gases would have been released into the air. Greenhouse gases contribute to global warming and acid rain, as well as global climate change.

Nuclear power plants do not combust fuels that release greenhouse gases into the air, but they do create surmountable waste as a result of fission and radiation. Nuclear plants in the United States alone create 2,000 metric tons of high level radioactive waste, and 817 metric tonnes of low level radioactive waste each year (refer to figure 3). This waste still contains radioactive material such as plutonium and uranium, and will need to spend decades to spend its half-life process. As of 2015, entire Nuclear power industry has produced 76,430 metric tons of spent nuclear fuel on site.

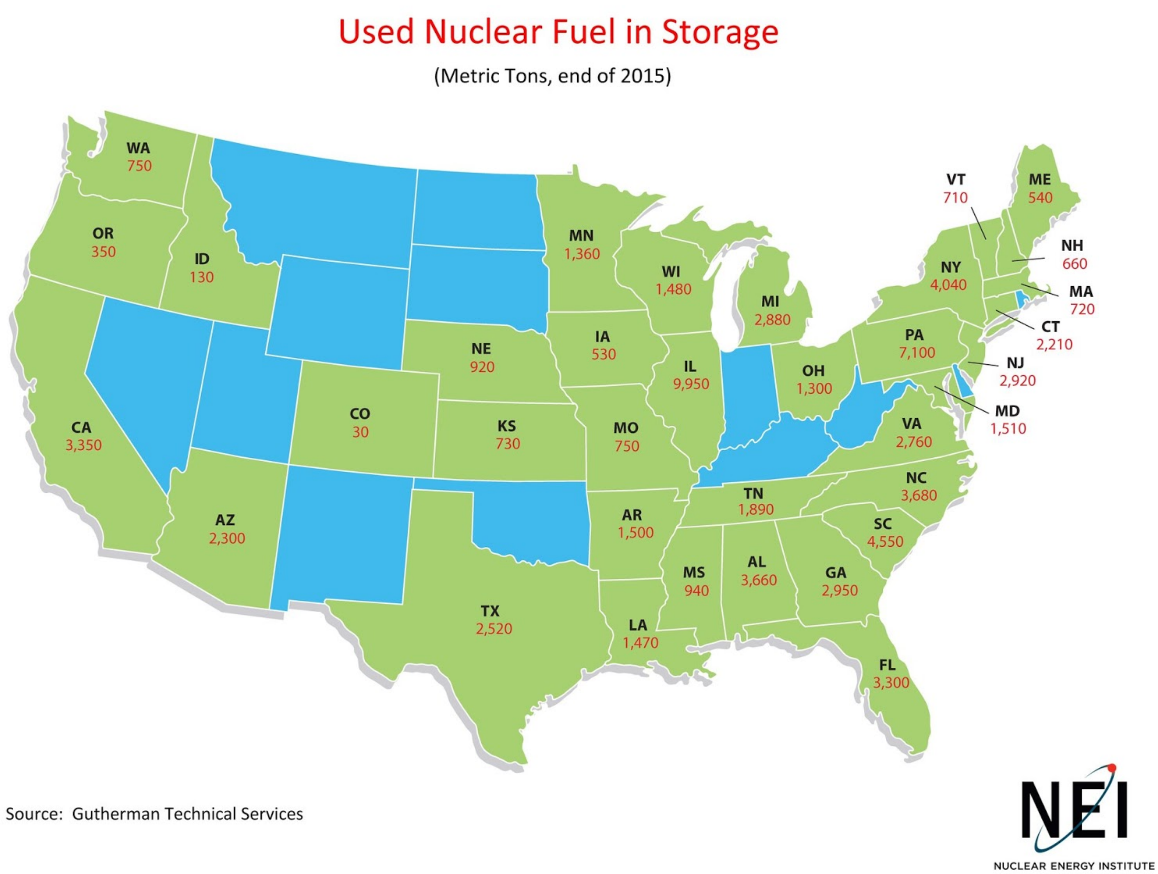

Figure 3

Explanation of Nuclear Technology

Nuclear technology is the energy released by splitting the atoms of specific elements. During the Second World War, the bombs released a lot of energy by splitting the atoms of particular isotopes of either uranium or plutonium. Nuclear energy is the energy in the nucleus of an atom. A nuclear reactor is a series of machines that can control nuclear fission to produce electricity. The fuel the reactors use to produce nuclear fission are little pellets of uranium. The uranium is forced to break apart, releasing fission products. The fission products cause other atoms to split, resulting in a chain reaction. Nuclear energy produces electricity that is used to power homes, public offices, businesses, and hospitals (refer to figure 4). The first commercial nuclear reactor used to make electricity was located near Arco, Idaho, in 1951.

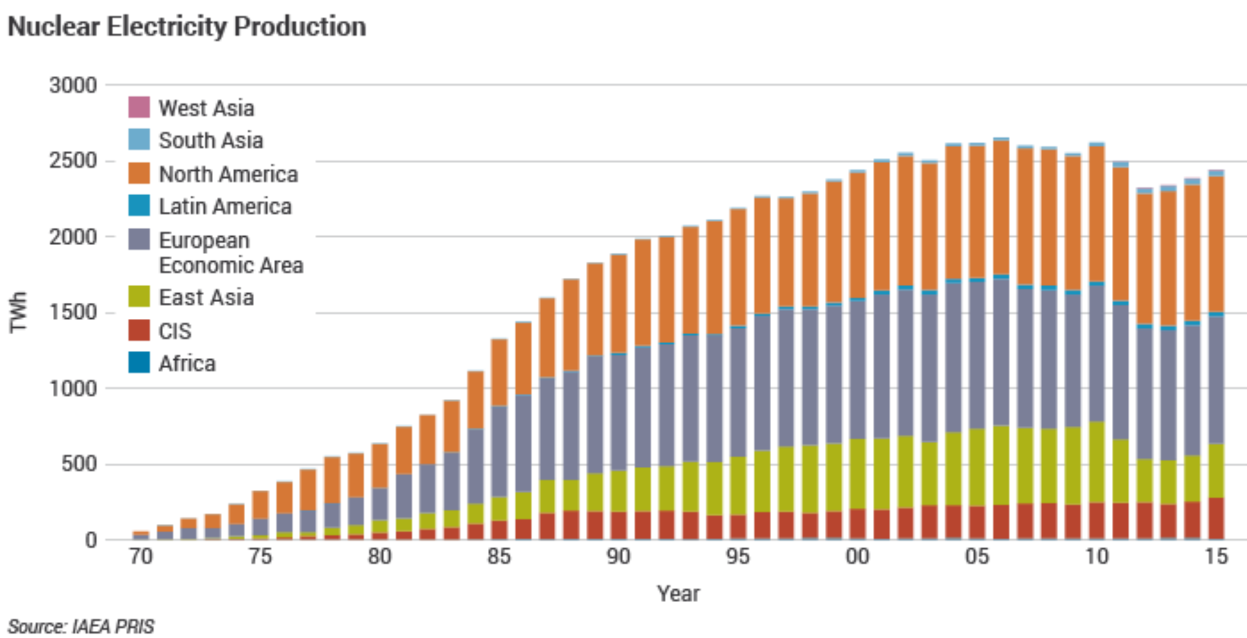

Figure 4:Nuclear Energy Production throughout the world

Nuclear power plants produce clean energy. They don't create greenhouse gases that pollute the air. It doesn't matter where they are built, because the environment is not noticeably altered, though they do need to be by a source of water for cooling. However, radioactive material is left over from the operation of a nuclear reactor. "Nuclear power could provide energy security for the UK and produce far less carbon dioxide than fossil fuels, but the waste it produces is potentially very dangerous if not handled properly," said Professor Steve Liddle, Co-Director of the Centre for Radiochemistry Research at The University of Manchester. "In order to find ways of reducing the volume of nuclear waste and recycle unspent fuel, research has focussed on developing our understanding of how radioactive actinide elements interact with elements from around the periodic table that they could come into contact with in the fuel cycle." (Student's) Radioactive material is a collection of unstable atomic nuclei. This material can be extremely toxic, causing burns and increasing the risk for cancers, blood diseases, and bone decay. The leftovers from the operation of a nuclear reactor is called radioactive waste. It is mostly clothing worn by the workers, tools, and cloths that have been in contact with the radioactive dust. This radioactive dust can keep the clothes and tools radioactive for thousands of years. The first commercial nuclear power stations started operation in the 1950s. Currently, there are over 440 commercial nuclear power reactors operable in 31 countries, with over 390,000 MWe of total capacity. About 60 more reactors are under construction. They provide over 11% of the world's electricity as continuous, reliable base-load power, without carbon dioxide emissions. 55 countries operate a total of about 245 research reactors, and a further 180 nuclear reactors power some 140 ships and submarines.

Light Water Reactors

The most common type of nuclear power plant is called a Light Water Reactor (LWR). LWRs make up all of the nuclear reactors in the United States. There are two types of LWRs, the pressurized water reactor, and the boiling water reactor. The pressurized water reactor is the most common in the United States (Nuclear).

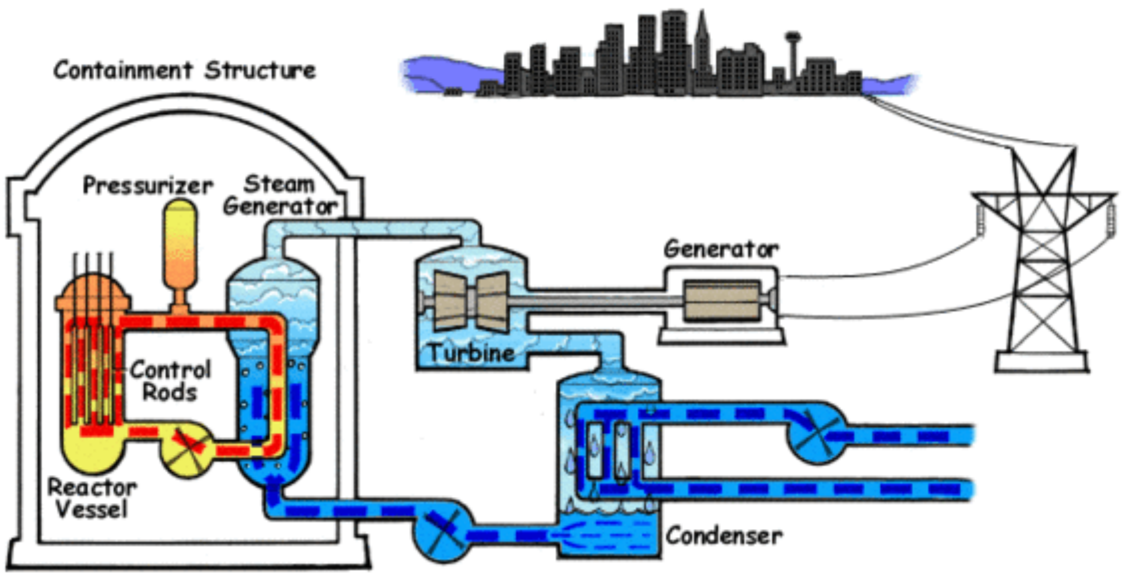

Figure 5: The basic design of a LWR

The main section of a LWR is called the reactor vessel (refer to figure 5). The reactor vessel is where the nuclear reactions occur and where the heat is generated, but more on the reactor vessel in a minute. The heat from the reaction is transferred to the water, which is also the coolant, and then pumped to a heat exchange where it heats a separate section of water that then turns to steam and turns a turbine to generate electricity. The steam is then pumped through a condenser where it goes from being a gas to a liquid again and the cycle repeats. In the condenser, regular water is used, usually from a river, lake, or ocean, and then either pumped back where it came from, or released as steam into the atmosphere (Light). LWRs run at over 150 atmospheres (2,250psi) of pressure, and at about 350C (Pressurized).

In the reactor vessel is the fuel rods and the control rods. The fuel rods are hollow rods made of zirconium. Inside the fuel rods are uranium fuel pellets, enriched to 3% uranium-235, while natural uranium is 0.7% uranium-235. These fuel rods are usually about 12 feet long, are about as thin as a pencil, and are put into bundles. There are 179-264 fuel rods per bundle, and 121-193 bundles of fuel rods inside the pressure vessel. The reactor needs to be refueled every

12-18 months, where one fourth of the fuel is replaced (Light). When the fuel is removed, there is still about 97% of the original energy left in the fuel, this is why the waste is so dangerous (TEDxNewEngland). Also inside the reactor vessel is the control rods. The control rods are the same size as the fuel rods, but are filled with either hafnium or cadmium. The control rods absorb some of the neutrons so that they cannot be part of the reaction. This slows down the reaction for when less energy is needed, and can be moved to generate more or less power (Light).

Another important thing to understand about a LWR is the function of the water. The water acts as both a coolant, and a moderator. A moderator is a chemical or element that slows down the neutrons in the reactor, so that it is easier to be used for fission. Though the water also absorbs neutrons, making the reaction more difficult. This is why you must used enriched uranium in a LWR (Light).

An issue with LWRs is load following. Load following is just changing the amount of power the reactor produces. The issue with a LWR doing this is called xenon poisoning. This occurs when iodine decays into xenon. This is a regular process in a LWR, but does have issues. Xenon is one of the best elements for absorbing neutrons, so it will slow down the reaction. After a period of time, the reactor will reach an equilibrium where the amount of xenon being generated and the amount decaying is the same. When power is increased in the reactor (remove some of the control rods), the amount of xenon decreases, making the reactor go even faster. When power is decreased the amount of xenon increases, making the reactor generate even less power. These effects of xenon posing make changing the amount of power a LWR very difficult, especially since it can take up to 50 hours for the levels of xenon to reach equilibrium after a control rod shift (Neutron).

The next part that is important to understand about a LWR is decay heat. Decay heat is the heat generated from the fission byproducts after the reactor has been shut down. The decay heat is not as strong as when the reactor is running, but still generates about 5% of the rated reactor energy. It also takes between 1-3 years to completely cool off. During this time period the fuel rods need to have circulating water to keep them cool. If it gets too hot (above 2,000C) then it can break apart the water to O_2 and H_2, which can then make a chemical explosion and release radioactive material to the environment (Light).

The last important part of a LWR is the waste it produces. Nuclear waste can be dangerous for well over 100,000 years, and as of yet, we still don't know what to do with the waste. This means that many LWRs have spent nuclear fuel (SNF) being stored around the power plant waiting for a solution. This SNF presents a nuclear proliferation risk as well as increasing the risk of being released into the environment, and LWRs produce over 44,000 lbs of high level nuclear waste each year (TEDxNewEngland).

Thorium Fuel Cycle

Thorium is chemical element number 90, and it was named after the Norse God, Thor. Thorium is found in small amounts, but it is much more abundant in nature than uranium is. Seeing as we have a limited amount of uranium that can be found. The thorium fuel cycle uses the isotope of thorium-232, as the fertile material in a nuclear fuel cycle. Since it is fertile rather than fissile, it can only be used as a fuel in conjunction with a fissile material, like recycled plutonium. When thorium absorbs a neutron, it will transmute into uranium-233 (U-233). Thorium fuels need a fissile material as a driver, so a chain reaction can be maintained. The only fissile drivers available are U-233, U-235, and plutonium-239 (Pu-239), which are all difficult to supply. Since you need a fissile driver and a fertile material, thorium is a wonderful option to use.

Molten salt reactors are well suited to thorium fuel, because normal fuel fabrication does not occur. Thorium fuel cycles also offer lower levels of waste generation, less transuranic elements in the waste, and provides a different option for nuclear fuel supply. The stability of thorium is unsure. Before thorium will be able to be used widely throughout the world, lots of testing, analysis, licensing, and qualification work is required. The testing is expensive and will not be successful unless the government supports it. There are no real incentives for investing in a new fuel type that might save uranium resources. The fuel fabrication and the cost of reprocessing is greater than when using uranium.

The USA produced two tons of U-233 from thorium during the cold war, at many different amounts of chemical and isotopic purity. It is possible to use it in a nuclear weapon, but since “the production of U-233 inevitably also yields U-232 which is a strong gamma-emitter, as are some decay products such as thallium-208 ('thorium C'), making the material extremely difficult to handle and also easy to detect.” (Thorium) This means that nuclear weapons would be more easily detected than what we have right now.

One nation that is planning on using the thorium fuel cycle is India. They have easily accessible thorium, and relatively little uranium available to them. They plan on using pressurised heavy water reactors (PHWRs) and light water reactors, fuelled by uranium, which will produce plutonium that is to be used in fuels in its fast reactors and advanced heavy water reactors. India will use fast breeder reactors (FBRs) and use plutonium-based fuel to make their plutonium inventory bigger. The blanket around the core will have thorium and uranium so Pu-239 and U-233 is produced. The advanced heavy water reactors (AHWRs) will then burn thorium-plutonium fuels, to breed U-233, which will eventually be available for use as a self-sustaining fissile driver for breeding AHWRs.

Thor Energy is developing a nuclear fuel technology, using thorium instead of uranium. They have developed "an advanced thorium based oxide fuel." (Towards) Their goal is to qualify the thorium fuel for use in future generations of light water reactors. As of now, Thor Energy has not found a reason for thorium not to be used in light water reactors. They believe that in the long-term perspective, thorium fuels can provide access to improve the status of nuclear energy. This will be done by, "Achieving more sustainable energy generation in which mined nuclear material is used more effectively." (Towards) This provides the possibility for high conversion, and breeding of U-233 from thorium fuels. Thorium fuels will also provide access to improve the status of nuclear energy by, "Employing fuels that generate less problematic waste streams, and that can also transmute (destroy) actinide components in current-generation thermal reactor systems." (Towards)

Future of Nuclear Power

Since the age of commercial nuclear power began, we have been stuck in the same loop of making the same type of Light Water Reactor (LWR) with the same issues. In fact, every single commercial nuclear power plant in the United states is an LWR (TEDxNewEngland). I think it's time that we stop looking at what we've done, and start looking at what we can do. I think that the future of nuclear fission is knocking on our door, and all we have to do is open the door to new technologies.

I think the first type of reactor that the future holds for us is what are called Small Modular Reactors (SMRs). In order to be considered a SMR, it has to generate less than 300 Megawatts of Electricity (MWe). The advantage to SMRs is that they can be built in a factory for much cheaper, and then shipped out to where they are needed. They would need a minimal workforce, and usually do not need to be fueled very often. They are also really good at changing the amount of electricity they produce, so they can change to meet demands (Small). Another use for SMRs is to put them on commercial transport ships. With a SMR on board, they would not need the large amounts of fuel to move and power the ship. The military has already proven that having a nuclear reactor on a ship is not dangerous, if managed properly. In fact, it may even be safer than on land at times because you have easy access to water to cool the reactor if it ever overheats. SMRs can differ greatly in design, some are just smaller versions regular sized reactors, and some are new technologies entirely.

Another technology that I think can change the nuclear industry is actually an older one, the Molten Salt Reactor (MSR). MSRs were first designed at Oak Ridge National Laboratory in Tennessee, in the late 50's, but since about the 80's, there hasn't been much interest in MSRs (Molten). Until now, but first let's look at what an MSR is, and how it works.

The biggest difference in an MSR versus a LWR is that the coolant is not water, but is a molten salt. The fuel for an MSR, instead of being in pellets in ceramic tubes, is in the coolant itself. The fuel can either be in solid form in pellets in the fuel, or more commonly, be a liquid dissolved into the coolant itself (Molten). The rest of the system is pretty similar to an LWR. The main coolant is moved to a heat exchanged that intern heats water and turns a turbine to generate electricity. Another key difference is that most MSRs have a safety seal on the bottom. The seal is electrically cooled salt, that will melt if the reactor gets too hot or loses power (what happened in Fukushima). When the seal melts, the coolant and the fuel are moved into an auxiliary fuel tank by gravity. In this fuel tank, the mixture is much more spread out, and over the course of a couple hours, will cool into a solid state. Reactors with this kind of feature are considered walk away safe. Where even if they lose all power, and all staff leave, the reactor will settle down and stop running without any damage done (Molten wikipedia).

The type of salts used are different with every design, though none use sodium chloride. There are different advantages to different salts, lithium salts are some of the best to use because they are good moderators (they slow down the neutrons in the reactor), but it has to be lithium 7, because lithium 6, when exposed to neutrons, produces tritium waste (hydrogen 3). Chloride salts are also good moderators, but need to be Chloride-37 to stop it from decaying into sulfur from the neutron bombardment. Fluoride salts are good because they can bond with Uranium to form UF4. Fluoride and Lithium salts also don't damage most common metal building materials, and are mostly unaffected by neutrons released during the reaction (though Li-6 will form tritium). Sometimes beryllium is used in the salts, but beryllium is very toxic, which makes leaks very dangerous, and regular maintenance is much more dangerous (Molten wikipedia). Another benefit of using molten salts over water is there is usually no hydrogen in the salts. This means that if the reactor does over heat, there is no buildup of hydrogen gas to cause a dangerous explosion and release the radioactive waste to the surrounding environment.

Another key advantage of MSRs is that they run at atmospheric pressure, rather than LWRs that can run beyond 150 atmospheres of pressure. This means that if there was a leak in the reactor, there would be no inclination for the radioactive materials to leave the core. Another advantage of this is it is a lot cheaper to build, since you do not have to strengthen everything to withstand over 150 atmospheres of pressure (Molten).

Another advantage of MSRs is that they run at much higher temperatures than LWRs. MSRs can run anywhere from 500C-1400C, but generally closer to about 600-700C. This makes MSRs more efficient than LWRs because less energy is wasted cooling the reactor.

Some of the last advantages of MSRs have to do with comparisons to normal LWRs. MSRs are much better at load following, in fact they can change it in about 60 seconds (Molten wikipedia). This is very difficult to do in an LWR, (Iodine). Another difference is the nuclear waste. MSRs produce much less nuclear waste then regular LWRs, and the waste itself is not weapons grade material (Molten wikipedia). The waste that is there is also not dangerous for as long as in a LWR. MSRs also are better at using different fuels, many are built to run off of thorium, which also produces less waste.

In conclusion, there is not a whole lot of bad to say about MSRs. They produce more power per cubic meter then LWRs, and are much more efficient in their fuel use while doing it.

Now let's look in more detail at specific MSR designs. The first one that I think has a major chance to change the future was designed by Taylor Wilson. Taylor Wilson is a 22 year old American Nuclear Physicist from Arkansas. In 2008, at the age of 14, he became the youngest person ever to build a nuclear fusion reactor.

Taylor Wilson spent a lot of time working on how to make this reactor not a nuclear proliferation risk, so it could be used in other countries. The first way he did that is the fuel. It can run on either down blended nuclear warheads, so the fuel is no longer usable in weapons. This is good because it helps get rid of the world's current stockpile of nuclear weapons, while also providing clean electricity. The reactor can also run on thorium if there is no other type of fuel available. The next thing he designed it to do is make it so it can go 30 years without needing to be refueled. This means that it can be buried underground where it will not be a terrorists or a nuclear proliferation risk. This protects the surrounding area because it does not present a nuclear proliferation risk, regardless of the setting of the reactor. (Taylor).

This MSR has several advantages about it. First it is a SMR, so it can be built in a factory and shipped to its destination. This makes it much cheaper to build, and much shorter construction time. This makes it so power companies who have stuck with LWRs, might now be willing to try a new technology because it is less of a upfront cost. This also makes it better for third world countries, and in the Ted Talk that it was announced in, Taylor Wilson even mentioned that it could be used to power a rocket to Mars, then a habitation once it gets there. (Taylor).

Now let's move on to more of the details about this reactor. It generates 50-100 MWe, which is enough to power between 25,000-100,000 homes. It runs at normal atmospheric pressure, so if there is a leak in the reactor, then there is no inclination for the radioactive substances to escape. This MSR runs between 600-700C, which makes it more efficient than a normal LWR, in fact it is about 45-50%, while a normal LWR is only about 30-35% efficient. Another change in the reactor to make it more efficient is it uses compressed carbon dioxide or helium instead of steam to power the turbines. The last thing to consider with this MSR is, like many others, it has a salt plug at the bottom, that melts and drains the fuel into a cooling tank if it ever overheats. This makes the laws of physics work with the reactor to keep it from overheating and causing problems (Taylor).

Normal light water reactors produce about 44,000lbs of high level nuclear waste each year. This nuclear waste can be dangerous for well over 100,000 years, and we still have not figured out what to do with it (TEDxNewEngland). That is where the Waste Annihilating Molten Salt Reactor (WAMSR) comes it. It is a MSR that can run completely off of the nuclear waste from regular LWRs. Before we get to the details of how the WAMSR works, let's look at who designed it. The WAMSR was designed by Mark Massie, and Leslie Dewan, they have between the two of them, a P.h.D in nuclear engineering from MIT, a bachelor's degree in nuclear engineering and in mechanical engineering from MIT, a masters degree in mechanical engineering from MIT, and a bachelor's degree in nuclear engineering from the University of Tennessee.

Now let's look at why we can power a nuclear power plant, on waste from an LWR. First, although it is considered waste, spent nuclear fuel (SNF) actually has a lot of energy left inside it. In fact, when the fuel is removed from a LWR, it has only used about 3% of the energy that is in it (TEDxNewEngland). Part of the reason for this is because the fuel is a solid in fuel rods, it can only stay in the reactor for about 18 months before needing to be refueled (TEDxNewEngland). A LWR does not need to be refueled because there is no energy left in the fuel rods, but because the rods that hold the uranium fuel pellets gets damaged by the radiation over time. Another reason that the WAMSR can use nuclear waste is that it was designed to be able to run with less enriched uranium. A normal LWR uses 3.5-5% enriched uranium-235 (How uranium), but the WAMSR can use it as low as 1.2% (The Science).

Now let's look more closely at the design of the reactor (refer to figure 6). There is a primary loop. In this section there is the molten salt and the fuel, this is the section that is generating heat, and this section is radioactive. The heat is moved by a pump at the bottom that keeps the salt fuel mixture moving. The primary loop is supposed to be at 650C, and the freeze plug at the bottom will melt if it gets above 700C, but more on the freeze plug later.

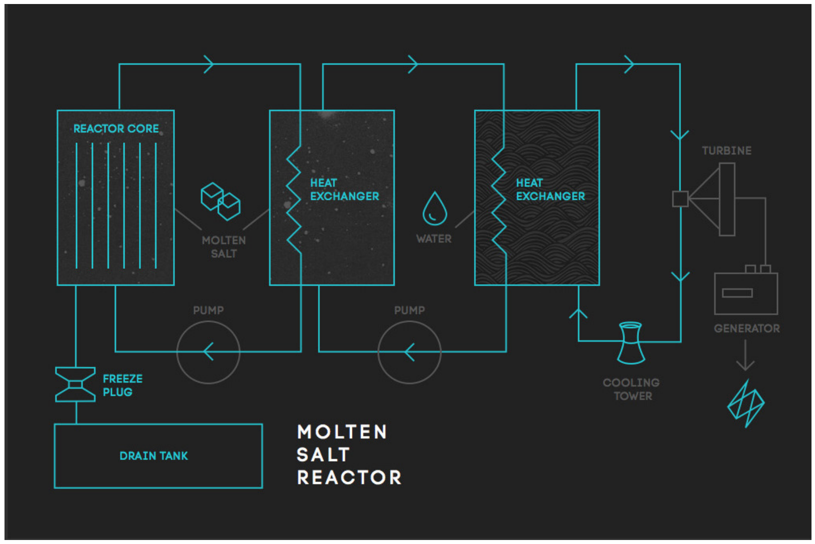

Figure 6: The design of the WAMSR (TRANSATOMIC)

The primary loop shares a heat exchanger with a intermediary loop, the intermediary loop contains different salts, and is not radioactive. This loop is also moved around by a pump, and shares a heat exchange with the power loop. The power loop generates power like any fossil fuel or nuclear power plant, makes steam that turns a turbine. This steam is then cooled and goes around to be heated up again to repeat the process. This is a basic summary of how it works, but I will go into more details on the safety features on it later (TRANSATOMIC).

The primary loop contains LiF as the coolant, and UF4 as the fuel. The lithium has to be mostly pure Li-7, but not completely. The WAMSR has a good off gas system to remove the tritium that it makes, so it can save money by not needing pure Li-7. However, the WAMSR does generate more tritium waste then a light water reactor, and almost as much as a heavy water reactor. The intermediary loop contains LiF-KF-NaF as the heat transfer to the power loop. The power loop just contains regular light water, but the designers are considering using high pressure CO2 in future designs to increase the efficiency of the reactor. Inside the power loop is the moderator. The moderators slow the speed of the neutrons to the speed needed for the reactor design. The WAMSR uses zirconium hydride, while most LWRs use water, though graphite is another common moderator. The zirconium hydride is good because it is better than graphite or water at slowing the neutrons, while also not chaining size under radiation damage like graphite can. It also does not absorb the neutrons like the water, which is part of the reason why the WAMSR can use low enriched uranium. This is good because it stops structure damage from the changing size and shape of the moderator as can happen in LWRs. (TRANSATOMIC).

The next thing to talk about with the WAMSR is nuclear waste and how it gets out of the reactor. There are three ways to remove nuclear waste from the WAMSR. First is the off gas system. This system gets rid of the wastes that are gases, which are xenon, krypton, and tritium, and stores them in compressed bottles on site. There is about 100 KG of this type of waste a year,

of which only about 50 grams is tritium. It is very important to get the xenon out of the reactor because xenon is the best element at absorbing neutrons, and this makes the reaction slow down. The next way to get rid of waste is a nickel metal mesh filter. This removes about 200 KG a year of, zinc, gallium, germanium, arsenic, selenium, niobium, molybdenum, technetium, ruthenium, rhodium, palladium, silver, cadmium, indium, tin, antimony, tellurium, and iodine. There is no information on how these wastes will be stored, but they will be in a metallic form. The last way of removing waste from the WAMSR is a new technology that takes the waste, chromium, iron, nickel, rubidium, strontium, yttrium, zirconium, cesium, barium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, and erbium, into an oxide form. This is then put into a processing facility that surrounds them in a ceramic that can be easily stored. With about half a ton of waste removed a year, the WAMSR needs to be refueled about half a ton each year, usually a lot of small batches of refueling (TRANSATOMIC). In summary, I think that the WAMSR has a great waste removal system that is able to keep the reactor functioning properly and safely.

The next step to talk about the WAMSR is the anti proliferation risk this is inherently built into how it works. The first is that it runs off of nuclear waste. This means that there is no need for new enrichments facilities for the WAMSR, even if there are a lot in use all around the world. The next is that the fuel will stay in the reactor for a lot longer. This means that there is less energy left in the fuel, but it also means there is no need for a reprocessing plant for the fuel. The last is that there won't be large stockpiles of SNF outside the plant, as there can be for LWRs. Though this is a nuclear power plant, so it will have some risks. First is that the stream of lanthanides (the waste removed via the new technology and stored into a ceramic) do pose a risk for creating nuclear weapons, but there are few of them compared to a regular LWR. The other risk is if thorium fuel is used. When thorium fuel is used, the reactor creates protactinium. The protactinium is then removed from the reactor where it will decay into uranium-233. This uranium while outside of the reactor does present a proliferation risk, whether by the people running the plant, or being stole. Though the uranium-233 will be put back into the reactor as fuel (TRANSATOMIC).

Now let's talk about the safety features of the WAMSR. The first line of defense is when the salts heat up, they expand. This results in less fission and the salts cooling back down. Another safety feature of the WAMSR is the pressure difference between the loops. Each loop is slightly more pressure than the one before it, so if there is a leak, the radioactive material will stay in the primary loop. If there is a leak in the secondary loop, then those salts would tend to stay in the secondary loop. The next line of defense is the freeze valve. There are freeze valves on both the primary and the secondary loops that will melt and drain the fuel and salts into a dump tank. This tank has a large surface area to spread out the salts, allowing them to cool to a solid in 1.5-3 hours. If the freeze valve were to fail, there is a shutdown rod to make the reactor sub-critical and shutdown. If that fails, then the zirconium hydride heats and separates, this takes away the moderator from the reactor, but will not produce enough hydrogen gas for an explosion, especially since there is no oxygen in the reactor. If the piping fails, then it will leak out, and be funneled into the cooling tank by gravity. If the radiative salts get out into the open air, they will cool into a solid very quickly, where they can then be dealt with in whatever way best suits the situation (TRANSATOMIC). In conclusion, the WAMSR has multiple redundancies to prevent any issues from occurring.

Next is how much power the WAMSR produces. The WAMSR produces 550MWe (The Science), and if all the world's SNF was used in WAMSRs, it could power the world for 72 years, including increasing demand (TEDxNewEngland).

The next thing to look at is how much it costs, and how long it takes to build. It is estimated to cost about $2billion, which is far cheaper than a LWR, and take about 3 years to build, which is shorter than a LWR. Fueling will also be cheaper since it uses nuclear waste. It is estimated that, including all the refining needed, the fuel will cost $440 per kilogram. This means that for half a ton a year will cost just under $200,000 a year in fuel costs (TRANSATOMIC).

The last part of the WAMSR to look at is how far in the future is it. The WAMSR is being developed by a company called Transatomic. According to the website, they are over halfway done with the third stage of development. In this stage, Transatomic is testing the long term durability of the building materials under the kind of environment they will be in, such as temperature and radiation. The sixth and final stage is building a fuel scale WAMSR, that will also be the first commercial product to be sold (What's Next). I think that the WAMSR, though still a few years away, is the next step in nuclear power in the 21st century.

Although these MSRs are a great hope for the near future, nuclear fusion is the main goal. Nuclear fusion gets its energy from combining atoms, rather than breaking them apart. The issue with fusion is that we have not been able to contain a continuous reaction where we get more energy from the reaction then we put into it. One of the main hopes of fusion is that it produces very small amounts of waste, and the only radiation it produces is ultraviolet light, which is sunlight (ITER).

There is currently a very large international project building a fusion experiment reactor in France, call the International Thermonuclear Experimental Reactor (ITER). ITER is run by the European Union, India, Japan, China, Russia, South Korea, and the United States. ITER is built to be the first fusion reactor where you get more energy from the reaction then you put it. It is estimated that they will use 50MW of energy, and gain 500 MW from the reactor, but this is still a far way away. It is supposed to be finished being built in 2019, and will start doing experiments in 2020. Full scale experiments won't be started until 2027. Although fusion power does look like a hopeful future, it is still far away.

Conclusion

Nuclear power is vast in opportunity and disaster. This paper highlighted how nuclear power originated and the events following suit to its discovery and possible uses it would undergo. To highlight the consequences, we took events that were victims to the expanse of nuclear power. We discussed the intricacies of what makes up nuclear power to point out the dangers and realities that come with harnessing such power, along with possible advantages it provides. To conclude our finding we ended by discussing the future uses nuclear power could have on the world if we continued to strive for new discoveries and applications. If you are interested in more information, then you can see the sources that we used below, and find any other information you are interested in.

Glossary

Nucleus: The center of an atom, contains the protons and the neutrons.

Fission: The process of breaking apart a nucleus of an atom, fission releases energy.

Fusion: The process of combining the nucleus of 2 or more atoms, this releases energy.

Fissile: Material that can undergo nuclear fission.

Fertile: Material that is not fissile, but can be converted into fissile material.

Transmute: Any process where the number of protons in a nucleus is changed.

Enrichment: The process of making a specific isotope (type of element) more common in a piece of material.

Reprocessing: The processes of separating the nuclear waste from usable fissile material.

Moderator: A chemical that slows down the speed of neutrons in a reactor.

Nuclear proliferation: The spread of nuclear materials, knowledge, or technology to countries that are not known as nuclear weapons states.

Lanthanides: Any atom with a atomic number between 57-71.

Actinide: Any atom with an atomic number between 89-103.

Transuranic: Any atom with a atomic number greater than 92.

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