THE STELLARATOR: UTILIZING NUCEAR FUSION AS A POWER SOURCE

JOL97@pitt.edu, MMT62@pitt.edu, JLM438@pitt.edu

Abstract*-Nuclear fusion, a process that could supply the world with endless energy with no harm to the environment, proposes a solution to our growing population and damaged planet. The process involves two isotopes of hydrogen, tritium and deuterium, which fuse together to form helium and release energy in the process. Because fusion converts a neutron from mass to energy as modeled by Einstein's* $E=mc^2$ *equation, the energy released during fusion can be larger than any other source used today. To achieve this, superconductors are used to create a magnetic field that suspends the materials until they reach the required temperature to turn the material into its plasma state. This plasma state allows the two atoms to collide and complete the fusion reaction.*

The Stellarator, a technological device engineers are developing in Greifswald, Germany, uses the process previously explained to create and harness energy for further use. Within devices used for harnessing this energy, a magnetic field must be created in order to suspend the plasma and ensure no contact between plasma and the carbon lining. Then, while controlling the temperature via microwaves and pressure within the vacuum tube, the plasma can be condensed and atoms with a high enough velocity fuse. With superconducting materials currently in use, engineers have reached a threshold where the magnitude of the electric field confining the plasma is constrained by current. ReBCO (Rare earth Barium Copper Oxide) is a super conductive technology that allows for higher currents and larger magnetic fields. Larger magnetic fields condense the plasma tighter and force more particles to collide. The evolution of more advanced superconductors will enable the Stellarator to create massive amounts of energy for the current generation, as well as generations to come.

Key Words—HTS (High Temperature Superconductors), magnetic fields, nuclear fusion, plasma, quantum tunneling, Stellarator, superconductors.

THE SCIENCE BEHIND THE STELLARATOR

Over time, society has developed various advances in the world of technology in order to improve our standard of living. While there are many ways to harness energy for use by the human population, scientists over the years have discovered issues with the power sources of the time. They work to modify the current technology in order to create more efficient and ethical methods. However, today we still find ourselves utilizing energy that damages our environment when harnessed. While science has come a long way from the days of coal and steam, a device that does not greatly harm the environment has not yet been developed. Due to the environmental crisis the earth is currently suffering, there is no better time than now for research in nuclear fusion to accelerate. The ability to use nuclear fusion as a global power source would not only stand as a massive leap for the scientific world, but the technology would transform the fate of the world we live in for generations to come.

Nuclear fusion is a process that allows for an extreme magnitude of energy to be created with minimal pollution to the environment. In nature, a process where the nuclei of small atoms collide in a reaction to bind together occurs, forming a super nucleus. When this occurs, large amounts of energy are released, which can be collected with various methods in order to generate massive amounts of electricity for use. When fusion takes place between deuterium and tritium, two isotopes of hydrogen, the energy produced is at its maximum. This is efficient when trying to collect the most product possible in the reaction. Unfortunately, the process of nuclear fusion has its complications and difficulties. The system must meet the necessary conditions for fusion to occur. The nuclei must be at the exact right speed and orientation in order to collide together. Because of how intricate the process of the two nuclei coming together must be, many total collisions must occur to be successful. This produces a large amount of energy that can be harnessed for use. Heating the material to its plasma state allows a great amount of collisions to occur between the atoms within the material. Additionally, in this state, the electrons lose their bond to the nucleus of their atom. This furthers the magnitude of the energy between the two nuclei in the collision and increases the efficiency of the process.

Materials at the temperatures reached by plasma are difficult to control, making the use of magnetic fields vital in order to gain control of such high energy levels that result from the temperatures. Magnetic fields control the current in the plasma, allowing it to confine and maintain the plasma and the interactions between the nuclei within it. Even with magnetic fields to control the plasma, the heat it produces still proposes an issue. Scientists have turned to superconductive materials in order to manage this issue. Materials with superconductive properties, such as Rare earth Barium Copper Oxide, enable a more efficient field to be created. Using these materials would increase the control scientists have over the plasma and further advance the process of fusion. Superconductive materials, magnetic fields, high temperatures, and many other elements come into play when discussing nuclear fusion.

If scientists want to harness this massive potential source of energy, they must create a device that can not only produce and capture the energy, but also withstand the conditions of the strong fields and hot materials needed for fusion to take place. This is exactly what engineers in Greifswald, Germany are studying with their development of the Wendelstein 7-x Stellarator. After many years of dedicated work and research, the Stellarator is one of the many devices they are designing that can harness the power of nuclear fusion. While science still has a long way to go before nuclear fusion can become as popular as other power sources, with the efforts of engineers around the world, nuclear fusion is expected to make contribution to the electricity grid by 2050 [1]. For scientists to fully understand the Stellarator and further understand nuclear fusion itself, examination of the device in Greifswald, as well as its successes and failures, will allow for a greater understanding of the Nuclear Fusion process.

HOW THE STELLARATOR FUNCTIONS

The Stellarator as a nuclear power source is still not very practical. For example, The Wendelstein 7-x, built in Greifswald, Germany and completed in 2015, uses a much greater amount of power than it produces. Its purpose is to test the feasibility of the technology and its various components as it relates to power generation. A Stellarator tries to replicate the extreme conditions inside the core of a star, an environment which is completely unlike any of which naturally occurs in this solar system outside of the Sun. In many stars, including the Sun, nuclear fusion is the main energy source and powers the life of the star. It does so by using superconducting magnets to produce a magnetic field which suspends a plasma where the fusion reaction takes place. The plasma’s extremely high temperature - in the region of 100,000,000 Kelvin - means that there is no known material which can confine it, which is why it must be suspended magnetically in a vacuum [1].

The main challenge is that for a superconductive material to operate optimally, it must be at a very low temperature. The threshold for the superconductive material used in the Wendelstein 7-x is 77 Kelvin. Ideally, the temperature would be around 4.2 Kelvin, but that is a lot more difficult to achieve. To illustrate the presence of a substance that is extremely hot, one can see the difficulties that come with keeping the magnets cool enough to generate the magnetic field required to keep the plasma suspended. The way the magnets are kept cool is that they are submerged in a bath of liquid helium in a cryostat to keep them as cold as possible.

The way the heat is generated In the Wendelstein 7-x is that the plasma will be heated up by 10 Megawatts of microwaves, which would result in 80 Megajoules of energy heating up the plasma. Other methods include neutral beam injection, which could last 10 seconds and supply another 80 Megajoules in total. The more energy which goes into the plasma, the hotter it gets, and the more ideal the conditions are for nuclear fusion.

Quantum tunneling

The Stellarator’s function is essentially to produce the conditions necessary for nuclear fusion, namely that which occurs between the hydrogen isotopes deuterium and tritium. The benefits of using these reactants is that they are and always will be extremely plentiful. The Stellarator fuses them by using a magnetic field and electric field to suspend a plasma which contains the reactants. Under extreme enough conditions, these reactants undergo quantum tunneling and fuse to make helium. When this happens, some mass is converted to energy in the process. The hotter and denser the plasma is, the more likely quantum tunneling is to occur, and as a direct result, the more likely nuclear fusion is to occur. The problem is that this is these are processes which happen inside the core of a star, and those conditions are extremely hard to replicate on Earth.

Quantum tunneling, in the context of nuclear fusion, is a phenomenon that happens when two nuclei overcome the electric (Coulomb) force that repels them from each other due to both being positively charged. It can be explained in part by the Schroedinger equation, which has to do with wave-particle duality. In essence, there is a nonzero chance that the particle has undergone quantum tunneling, and so sometimes it actually happens.

When quantum tunneling occurs, the strong nuclear force, which at extremely small distances such as a femtometer is much stronger than the Coulomb force and as such overpowers it, takes over and attracts the nuclei together so that they undergo nuclear fusion. In the case of elements lighter than iron, the difference in mass is converted to energy based on Einstein's $E=mc^2$ equation. Because c^2 is so great, even the conversion of small amounts of mass to energy results in the release of a relatively large amount of energy. Since the Stellarator fuses two hydrogen isotopes, this applies to the Stellarator, so the fusion reaction which occurs in it releases energy. Also, because the fusion reaction of two hydrogen nuclei is exothermic, the reaction can sustain itself in theory, meaning activation energy only must be overcome at the start.

The likelihood of quantum tunneling increases as the temperature of the plasma increases. This is because at higher temperatures, particles move with more speed, and thus are more likely to come close enough that there is a chance that they could quantum tunnel. Also, the density of particles in the plasma is extremely high, which means there are more particles to collide with. Higher temperatures also mean that there is more energy in the system, and since particles must borrow energy from the system in order to quantum tunnel, this also increases the likelihood of quantum tunneling [2]. It can be useful to picture this phenomenon as the particle, instead of using energy to get over a wall or hill, simply goes straight through it, borrowing energy from its surroundings to accomplish this. The height of the obstacle represents the amount of energy the particle should need in order to get over it. Without quantum tunneling, the particle would be unable to make it past the obstacle.

Another way of picturing quantum tunneling is to picture the probability of quantum tunneling occurring as a probability density function of energy. At some value on the horizontal axis, there is a vertical line, and everything in the region to the right of that line quantum tunnels. Another way of stating this is that some percentage of particles in the plasma will have enough energy to undergo nuclear fusion. The way to have a larger percentage of the area enclosed by the function exist to the right of the vertical line is to increase the temperature of the plasma. Simply put, as the temperature and pressure increase and the conditions inside the plasma become more extreme, more quantum tunneling will occur, so more nuclear fusion will occur, which is of course the goal.

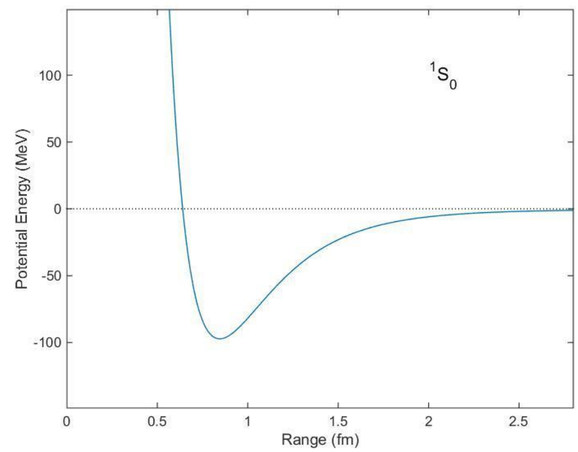

FIGURE 1 [3]
A graph of potential energy due to the nuclear force as a function of distance

Figure 1 illustrates how the nuclear force (mainly the strong force) brings nuclei together. Although essentially irrelevant at a distance of 2 femtometers, the strong force's potential well bottoms out at a distance of about 0.8 femtometers, and at that point the attraction caused by the strong force is much greater than the repulsive force caused by the Coulomb force. This also explains why the fusion of larger nuclei is endothermic: they are big enough that the distance between their centers is so great that the strong nuclear force barely acts on them. Hydrogen, on the other hand has a small enough nucleus that it can fuse exothermically. Going back to the high energy and subsequent high velocities of particles caused by the high temperatures inside of the Stellarator, those high velocities lead to more situations where there is a higher chance of quantum tunneling into this configuration and the nuclei fusing. In order to create these conditions, a plasma must be generated and suspended by a magnetic field.

Magnetic Fields

The generation of a very strong (3 Tesla) magnetic field is necessary to keep the plasma suspended [3]. To do this, superconductive loops are used. In the Wendelstein 7-x, there are 70 such loops, which must be kept at a very low temperature in order to conduct enough current to generate the magnetic field needed to suspend the plasma. A current of 12,800 Amperes is necessary for the coils to produce the required magnetic field.

To keep the plasma as dense as possible and in the right shape and structure, the 70 magnetic coils must be arranged very carefully. Below is the pentagonal shape of the plasma, and the locations of most of the magnets. Only 50 of the magnets are actually used to adjust the magnetic field. The goal of this is to compress the plasma to a density of $3*10^{20}$ particles per cubic meter. Higher density, of course, leads to more collisions and more fusion. In terms of keeping the plasma suspended correctly, the Wendelstein 7-x is relatively unique. It only has one magnet system, which both generates the electric field in the plasma and holds the plasma suspended.

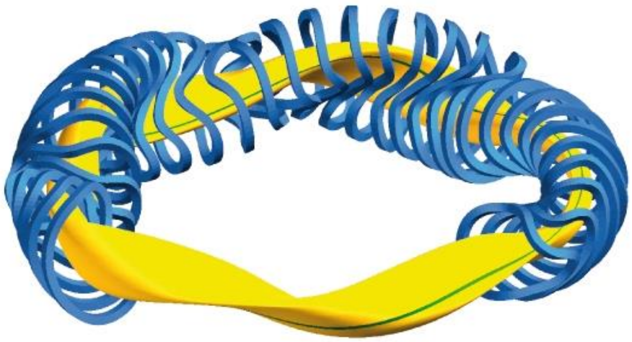

Figure 2 [4]
A computer illustration of the plasma (yellow) and the magnets (blue) in the Wendelstein 7-x

The magnetic field generates an electric field which is also very strong. This field helps confine the plasma and keep it as dense as possible [5]. When the plasma is denser, more quantum tunneling occurs. This, in turn, leads to more nuclear fusion reactions in the Stellarator. The magnetic and electric fields are both crucial to the suspension of plasma. Since the magnets generate the magnetic field, which in turn generates the electric field, they are doubly important in a way. They are solely responsible for suspending the plasma, and as such their performance is key for the performance of the Stellarator.

The way to maximize the performance of the magnets is to maximize the current which flows through them. The flow of charge in the superconductor is ultimately what generates the magnetic field. The magnitude of the magnetic field is related to the magnitude of the current. This means that the better a material is at conducting charge, the greater the strength of the magnetic field it can generate will be. A superconductor is more conductive in certain conditions, notably at colder temperatures. All of this means that the colder the superconductor is, the stronger the magnetic field is, and with a stronger magnetic field, the more fusion occurs. The great challenge with finding the right superconductive material is that it needs to be able to be kept cool even in the presence of extremely hot substances, in this case the plasma. Submerging the magnets in liquid helium in a cryostat helps with keeping the magnets cool. A cryostat is a bit like a refrigerator, but much colder, and is often used for the purpose of keeping something extremely cold. Even with a cryostat, it can be difficult to keep the superconducting magnets cold enough, so other ways are being tried as well.

SUPERCONDUCTOR TO INTENSIFY STELLARATOR ELECTROMAGNETS

Given the importance and functionality of magnetic fields in nuclear fusion processes, to advance this technology it is necessary to have more powerful electromagnets. Besides suspending the plasma, the magnetic fields have the job of confining the plasma. With increased confinement, high temperature plasma has an increased probability of fusion and therefore higher reaction frequencies and ultimately the production of more power. Basically, magnets are crucial in creating reactors that are efficient and sustainable. The magnetic fields created within the Stellarator are produced with coils of superconductive materials that, when exposed to large current and low temperatures, produce high magnitude magnetic fields. Though we currently use superconductive materials that can facilitate nuclear fusion in its earliest stages, we have reached a barrier. Rare-Earth-Barium-Copper-Oxides (ReBCO) holds promising solutions with increased current density, critical current, resistance to magnetic field degradation, (relatively) high temperature performance capabilities, affordability and tolerance to mechanical stress and strain in environments with increased pressure and forces.

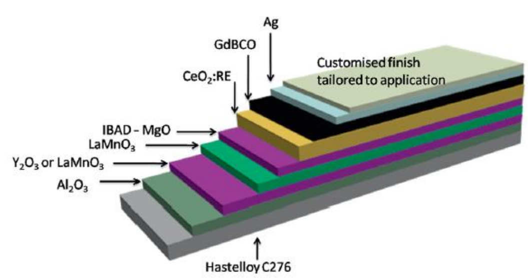

FIGURE 3 [6]
Composition of ReBCO tape in layers

Superconductors

Superconductors are the only materials capable of carrying currents large enough to produce magnetic fields that are strong enough to be used for nuclear fusion. The problem with traditional conductors is that as their temperature decreases towards absolute zero, resistance asymptotes to a value above 0 ohms, consequently maintaining some level of resistance. As superconductors decrease in temperature their resistance arrives at zero sometime before their temperature arrives at absolute zero.

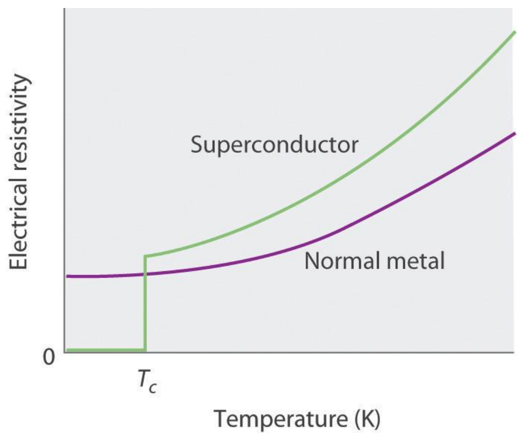

FIGURE 4 [7]
Graph of resistance as it changes with respect to temperature

Resistance gives normal conductors restrictions on current and decay that superconductors do not face because of their lack of resistance or internal magnetic fields. Even if there were a normal conductor with the ability to carry such required current, its properties and microstructure are such that it would degrade with tremendous speed, rendering is useless. ReBCO possesses decay constants that extend 1 billion years, making its decay theoretically nonexistent. From a maintenance stand point, such a material is appealing because of its permanence. Is will last forever, never having to be replaced or repaired. Superconductors and more specifically ReBCO meet and exceed the essential requirements for a material used in nuclear fusion. ReBCO is an important factor in developing and sustaining nuclear fusion.

Current Density and Critical Current

Current is a measure of the rate in which charge moves over time. A major benefit of ReBCO is that it offers higher critical currents. Materials with higher maximum currents that exhibit zero resistance effectively produce larger magnetic fields.

Current density is current per unit area. It describes how much charge moves through a cross-sectional portion of material over a duration of time. Current density relates the amount of current that a material transmits with the size of the material. ReBCOs such as Yttrium Barium Copper Oxide have high current densities, meaning that they don’t have to be large to carry high currents, in fact the actual superconductive material is contained within only 1-2 micrometers or 1% of ReBCO tape itself, a flexible application of ReBCO that acts as a wire substitute [6].

Properties

What separates these materials from other superconductors is their increased resistance to current density decay when exposed to external magnetic fields. ReBCO can sustain increased current densities while being exposed to larger magnitude fields. These conditions are where traditional superconductive materials would begin to sacrifice performance. This property is important for applications in the stellarator because there are multiple magnetic coils that simultaneously emanate magnetic fields, all contributing and receiving saturation from neighboring coils. As the magnitude of near fields increases, they parasitically affect the superconductors ability to carry current, therefore weakening the electromagnet.

This material is producing a critical current of 663 A/4mm and a current density of 1658 A/mm^2 with an applied magnetic field of 21 T at 4.2 degrees K. When the applied magnetic field is decreased to about 5 T, with the same temperature, current density increases to nearly 2500 A/mm^2. This is impressive considering its closest rival has a current density that peaks at about 1500 A/mm^2. Its lowest performing competitors, when exposed to applied magnetic fields that reach 21 T fail to exceed 100 A/mm^2 current density [8].

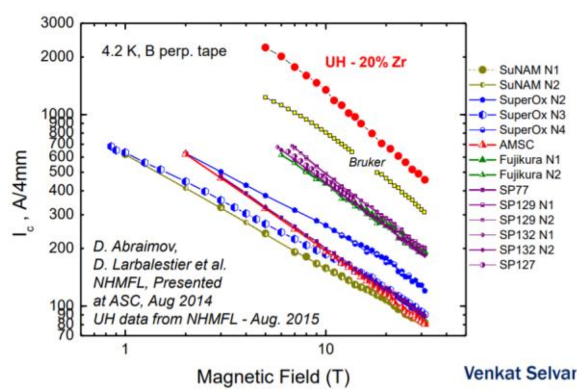

FIGURE 5 [8]
Graph of the variations in critical current as applied magnetic field changes

When Magnetic fields are applied perpendicularly to the orientation of ReBCO tape the degradation curve is flattened even more. The Current Density at 4.2 K increases to nearly 5000 A/mm^2 with an applied magnetic field of 5 T. Again, when the Applied magnetic field is increased to Nearly 32 T the current density decreases to just over 1000 A/mm^2. Once again showing the highest Current density with high applied external magnetic fields, amongst competitors is not as great [8]. The applied magnetic field is synonymous with interference from neighboring coils. Though temperatures inside the Stellarator would be higher, it is reasonable to conclude that given the performance gap between ReBCO and its competitors, scaling for higher temperatures, would render this gap constant and proportional, especially with the high temperature properties that it possesses. For applications such as the Stellarator we need a material that minimizes the magnetic field degradation.

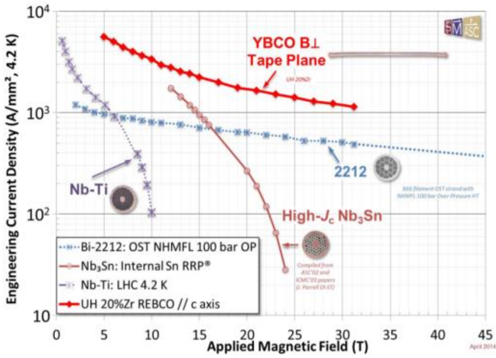

FIGURE 6 [8]
Graph of the variations in critical current as applied perpendicular magnetic field changes

High current density optimizes ReBCO to be a more affordable alternative to older superconductive materials. With higher current density, less material is needed to achieve an equivalent magnetic field to that of a material with a lesser current density because ReBCO can carry more current [9]. This also makes ReBCO more compact and light weight. ReBCO tape is also flexible, having a critical radius of 6mm [6].

The Stellarator has a very complex coil geometry, designed to twist the plasma as it gravitates. This design cultivates fusion longevity and plasma confinement. It is crucial that the material that they are composed of can conform to the curves of its geometry without compromising performance or structure. ReBCO is flexible enough to provide this ability. ReBCO is versatile in other ways as well.

The environment inside the Stellarator is inherently hot as a result of the fusion process. The plasma needs to be nearly 60,000,000 Kelvin to even have a chance of fusing. This is not good given that superconductive materials need to experience very low temperatures to exhibit zero resistance properties. This poses a problem that, fortunately, ReBCO has the solution to. The cryogenic compartment that surrounds the coils is still susceptible to heat exposure, despite its extremely cold conditions. This makes ReBCO, a high temperature superconductor, ideal for these conditions. YBCO has a relatively high critical temperature of 92 K and TIBCO has a critical temperature of 125 K. Both can carry sufficiently high currents at that higher temperatures. Though this is not its ideal operating temperature, ReBCO functions within the specifications necessary for fusion that is sustainable and contestant [6].

Conditions inside the Stellarator present intense magnetic forces which result in stress and strain on the components within the device, the superconductive coils included. It is important that this material is optimized for elasticity to retain charge density as it deforms. Though ReBCO has performed well compared to older superconductors, when exposed to stresses and strains, ReBCO's ability to maintain current density is attributed to its tolerance to elastic deformation. ReBCO tapes containing Hastelloy substrates, a high-performance Nickel Tungsten Alloy [6], fares even better with high irreversible strain limits when compared to tapes with different substrates [3]. This is important because thresholds for irreversible strain are directly correlated to irreversible reduction of critical current. Using a material like ReBCO could make nuclear fusion reactors capable of running longer and more efficiently.

THE FUTURE OF NUCLEAR FUSION POWER

The future of nuclear fusion depends on global efforts and efficient funding and research. Without both national and international efforts from scientists worldwide, the efforts to create the Stellarator with the most efficient nuclear fusion reactions may fail. This failure would cause numerous repercussions to both the EU and many other countries due to the cost and efforts they will have invested. The environment of the earth will also suffer from a lack of this power source. The environmental crisis that is currently being faced, with many scientists predicting that if no change in the sustainability of our energy and other devices permanent damage will ensue, can only be solved by global efforts to diminish the waste that the human society produces. Developing a nuclear fusion reaction with the Stellarator to a point where it is a reliable and efficient energy source could decrease the waste from alternative power sources, subsequently benefiting the environment. Overall, while the future of the Stellarator and other forms of nuclear fusion power may seem unattainable, efforts from scientists and nations across the globe could allow the dreams of many scientists to become a tangible reality [9].

Ethics of the Stellarator: A Mission That Must Successful

Nuclear fusion is a modern energy source that presents itself with large significance for the future of the environment of the earth. As demonstrated by the continual decrease in the state of the environment across the globe, the power sources used globally are causing great harm to the environment. Nuclear fusion is a form of producing of energy that would have little waste that would negatively affect our environment. However, like all reactions, some products do form during nuclear fusion that are not necessarily ideal. Due to the increasing attention to research of fusion in Europe, a large amount of information on how to manage the waste, as well as the costs and ethics of the device, is widely available.

Before scientists can begin developing the Stellarator and other nuclear fusion devices in an environmentally safe design, the costs of the materials and production of the device must be understood. By understanding the individual costs of each element to the product, how to reduce these costs and increase the efficiency, and the timeline of the project overall, scientists can work to advance each element to be as environmentally friendly as possible. Estimating the costs of power plants can be difficult and unclear because of the many uncertainties and fluctuations in costs and budgets. As explained by the European Fusion Development Agreement, designing a budget plan that has the most room for error is essential in order to budget the project properly and avoid a shortage of funds. Funding for the project must be provided by national and international sources, with additional smaller funding supplied by industries involved. Since fusion power is a new development and research is still being conducted, the costs are extreme. An estimate of hundreds of millions of Euros would be required to accelerate the research being conducted by the EU and allow for DEMO, or the DEMOnstration Power Station which is a team who have been developing nuclear fusion technology and devices, to complete their design. Furthermore, the testing facilities and modifications that will be applied to the DEMO design will add to this cost, with the final of the design totaling to at least 10 billion Euro. While these prices are intimidating, there are a variety of factors that should encourage the EU to stay in the race for nuclear fusion power using the Stellarator, both politically, and environmentally [10].

The EU has already presented the ITER project, which focuses on ambitious power sources and technology development for such power, to the public, with numerous documents and publications detailing their scheduled efforts for the next thirty plus years. If the EU were to withdraw from their plans, which they have made clear to be a major interest and concern of theirs, the political repercussions would be damaging. International partners, especially those who have funded the project, will lose their trust and sense of cooperation with the EU as an international partner as the EU will have backed down from a project. The integrity of the EU will be lost if they are to back out of this project, and this is something they cannot afford. Due to this, it is extremely likely that the EU will not back out of ITER, and they will attempt to finish the project to the best of their abilities in order to preserve their image. Not only will the political consequences be damaging to the EU, but they will also face the economic and technological repercussions that follow an uncompleted project [10].

Due to the amount of work and time that has already been put into the project, the failure of the technology would be a disastrous cost. The EU would miss out on completing a large project on futuristic energy, and millions of investments will have gone to waste. Additionally, the EU could likely be subjected to what is known as the knowledge drain. Many of the countries who have partnered in the development of nuclear fusion power sources, as well as their competitors, would use the failures of the EU to advance their own technologies and finish the race to new power sources before the EU. This would cause many scientists, engineers, and programs based in Europe to relocate to other areas where the studies are being continued, leaving Europe with a “drained” amount of knowledge in the subject. This would be detrimental to any further attempts in the field due to the lack of local scientific effort towards the subject. It is crucial that the EU continue with their efforts of the ITER project to avoid the many damaging effects that the uncompleted project would cause.

Nuclear Fusion Power: An Essential Element in the Efforts to Rebuild Our Environment

Waste is inevitably produced by sources of power due to excess products during reactions. For nuclear fusion, the main contribution thus far has been the need for disposal of many reusable gloves, garments, and other housekeeping waste due to contamination. However, due to further research explained in the document by the European Fusion Development Agreement, this problem may shrink greatly. This will happen if the original isotopes planned for use in nuclear fusion, hydrogen isotopes, are used in the process, the contamination can be resolved. The technique involves heating the waste in order to enable the separation of the molecules and hydrogen isotopes. Palladium silver alloy membranes, which are only permeable by the hydrogen isotopes, can be used to collect the tritium via carrier gas in the form of tritiated water vapor. The vapor will collect within tubes of the membrane, allowing only the hydrogen isotopes to pass through to the other side. This process not only rids the environment of the waste produced, but even increases the efficiency and cost of the nuclear fusion devices. The recollection of tritium allows for reuse, and the advancements made to the process have made the process efficient and cost effective [10].

Besides the waste being produced by the large amounts of research going into the technology, nuclear fusion produces the least possible waste for the environment. This power source presents itself as the only truly sustainable option for massive energy production for decades to come. Additionally, with extended research after the first successful production of fusion power plants, developments in the energy will advance the technology in order to pave a steady path for energy in the future. Nuclear fusion energy would provide an unlimited supply of inexpensive fuel with essential environmental safety. The energy would produce no harmful amounts of carbon dioxide or other atmospheric pollutants. While these may seem comparable to nuclear fission, there is a final advantage this energy source presents: short-lived radioactive products. The radioisotopes produced by fusion have an average half-life of less than ten years, ensuring that the radioactivity of the material will have diminished to a completely safe amount within 100 years, significantly faster than those produced by fission. For this reason, nuclear fusion evidently stands as the most essential form of energy production for the future [10].

The Stellarator: The Answer to the Future of Energy Production

The Stellarator and the advancements it has made in modern technology created a new wave of energy sources for upcoming generations. Energy presents itself as complicated, advanced, and extremely technical. However, scientists and engineers across the globe have been working for years to finally harness this energy. While the research they are conducting have allowed the scientific world to understand the problems and issues that nuclear fusion brings up, it has also allowed them to solve this issue using efficient methods, overall creating a more successful and brilliant project. The Stellarator, the ideal example of this power source, allows the world to understand just how brilliant this form of energy can be. With the minimal waste it produces, along with the masses of power it allows engineers to harness, the future of the world depends on this modern, clean, and intense energy form. As nations continue to come together in funding such a project, engineers have faith that their work will be astonishing, revolutionary, and a large leap for science as we understand it.

SOURCES

[1] "Nuclear Fusion - Tokamak VS Stellarator" QuaQuark. 11.13.2015. Accessed 1.25.2019.

[2] "Quantum Tunneling and Uncertainty Principle" The Physics of the Universe. Accessed 02.07.2019. https://www.physicsoftheuniverse.com/topics_quantum_uncertainty.html
https://www.youtube.com/watch?v=vqmoFzbZYEM

[3] C. Barth. "Electro-Mechanical Properties of ReBCO Coated Conductors from various Industrial Manufacturers at 77 K, self-field and 4.2 K, 19 T." Department of Condensed Matter Physics (DPMC), University of Geneva, Switzerland. 02.24.2015. Accessed 02.07.2019. https://arxiv.org/pdf/1502.06713.pdf

[4] "Concept Planning" Max Planck Institute for Plasma Physics. Accessed 03.28.2019 https://www.ipp.mpg.de/2815232/konzeptentwicklung

[5] "G2 HTS Wire" Super Power Inc. Accessed 02.07.2019. http://www.superpower-inc.com/content/2g-hts-wire

[6] T. Benkel "ReBCO tape performance under high magnetic field". G2Elab/Institute N´eel.11.23.2016. Accessed 3.7.19. https://www.epjap.org/articles/epjap/pdf/2017/09/ap160430.pdf

[7] "General Chemistry: Principles, Patterns, and Applications"2012.Accessed 03.28.2019.https://saylordotorg.github.io/text_general-chemistry-principles-patterns-and-applications-v1.0/s16-07-superconductors.html

[8] X. Wang "ReBCO accelerator magnet development: status and plans." U.S. Magnet Development Program. Accessed 3.7.2019 https://conferences.lbl.gov/event/73/session/2/contribution/6/material/slides/3.pdf

[9] "Nuclear Fusion Power Generation" Strategic Energy Technologies Information System. 2011. Accessed 01.15.2019. https://setis.ec.europa.eu/system/files/Nuclear_Fusion.pdf

[10] "Fusion in Europe - Quarterly News & Views on the Progress in Fusion Research." European Fusion Development Agreement. 2012. Accessed 01.15.2019. https://www.eurofusion.org/fileadmin/user_upload/Newsletter/Archive/EFDA%20Fusion%20in%20Europe/EFDA%20Fusion%20in%20Europe%202012%20Sep.pdf

ADDITIONAL SOURCES

S. Montgomery. "Why nuclear fusion is gaining steam – again." The Conversation. 04.09.2019. Accessed 01.15.2018. http://theconversation.com/why-nuclear-fusion-is-gaining-steam-again-93775

"Fusion Electricity - A roadmap to the realization of fusion energy." European Fusion Development Agreement. 11.2012. Accessed 01.15.2019.

"About Superconducting Wire" Superconductor Technologies Inc. Accessed 01.25.2019. https://www.suptech.com/about_superconducting_wire_n.php

"How hot is too hot in fusion?" Oak Ridge National Laboratory. 06.27.2017. Accessed 01.15.2019. https://www.olcf.ornl.gov/2017/06/27/how-hot-is-too-hot-in-fusion/

"Breakthrough in Nuclear Fusion? - Prof. Dennis Whyte" MIT Club of Northern California. 02.25.2016. Accessed 01.25.2019. https://www.youtube.com/watch?v=KkpqA8yG9T4

"About Superconducting Wire" Superconductor Technologies Inc. Accessed 01.25.2019.

https://www.suptech.com/about_superconducting_wire_n.php

"How hot is too hot in fusion?" Oak Ridge National Laboratory. 06.27.2017. Accessed 01.15.2019. https://www.olcf.ornl.gov/2017/06/27/how-hot-is-too-hot-in-fusion/

A Sundaram. "2G HTS wires made on 30 μm thick Hastelloy substrate"11.15.2016 Accessed 3.7.19

P Chaddah. " Critical current densities in superconducting materials". Cryogenics and Superconductivity Section, Centre for Advanced Technology. 04.2003. Accessed 3.7.19 https://www.ias.ac.in/article/fulltext/sadh/028/01-02/0273-0282

L.Cooley I. Pong "Cost drivers for very high energy p-p collider magnet conductors" Future Circular Collider.2016. Accessed 3.7.19 https://indico.cern.ch/event/438866/contributions/1085142/attachments/1257973/1858756/Cost_drivers_for_VHEPP_magnet_conductors-v2.pdf

" High-Performance, Low-Cost Superconducting Wires and Coils for High Power Wind Generators". University of Houston. Accessed 3.7.2019 https://arpa-e.energy.gov/?q=slick-sheet-project/low-cost-superconducting-wire-wind-generators

"Critical Temperatures for Superconductors". Hyperphyics. Accessed 3.7.2 http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scond.html

" Transition Temperatures in Yttrium Barium Copper Oxide (YBCO)" Worcester Polytechnic Institute. 2.24.2015. Accessed 3.7.19

ACKNOWLEDGEMENTS

As engineers, writing has not always come easy to us. We would like to acknowledge Joshua Zelesnick, our writing instructor for this assignment. Through multiple revisions and comments in email, he has helped us to put our ideas into words with this assignment. We will carry these skills gained from his constructive criticism with us through our academic and further careers in order to make our mark in the engineering world.

We would also like to acknowledge John Toner, who helped in brainstorming ideas for this assignment. After Megan Toner mentioned this assignment to him, he was eager to send multiple emails of ideas of innovations for mechanical and electrical engineering. After multiple phone conversations with him about the articles he was interested in, he presented the idea of nuclear fusion to Megan. After discussing with the group, we knew from our immediate interest in the topic that this innovation was ideal for our assignment.

Lastly, we would like to acknowledge our high school physics teachers, who originally grasped our attention with our first engineering courses. The ideas they presented to us in class were the catalyst for our growing interest in the broad and fascinating field. Without them, none of us would be in the Swanson School of Engineering today, and we are forever thankful for introducing us to the ideas that we would eventually learn to create.