

Migration of Energy Production to Nuclear Fusion

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Abstract. In stellar bodies, its gravitational force pushes atoms together fusing them, causing Nuclear Fusion to occur, so that the extra mass is converted into pure energy by Albert - Einstein's $E = mc^2$ mass-energy equivalence formula. On Earth, temperatures around 150 million degrees Celsius (average particle kinetic energy around 10 keV) are required to overcome Coulomb's law, the force between two charged particles, so that the fusion can occur. The preferred fuel source is Helium-3, found in abundance on the moon, due to its clean nature and energy output. In the future, Nuclear Fusion could play a role as the main form of electricity production once the proper infrastructure is built.

Keywords: Nuclear Fusion, Electricity Production, SpaceX, Energy

1. Introduction

Nuclear fusion is the form of energy production found in stellar objects. Nuclear fusion occurs when a star uses its large volume to force atoms together to fuse, and as a result, the excess mass must be converted into energy due to Albert Einstein's mass-energy equivalence formula eq. 1.[1, 2]

Equation 1:

$$E = mc^2$$

Equation 2:

$$Q = \frac{\text{fusion power output}}{\text{power input}}$$

E stands for energy, m stands for mass, c is the speed of light.

The size of the star determines which fuel sources can be used. That means that stars start with hydrogen, and then once all of the hydrogen atoms have formed helium, they begin fusing helium together, and they repeat this process until they have iron. However, no matter the size of the star, the Q value in eq. 2 cannot be less than 1. This means that more energy is expended in producing power than is being produced.[11, 3, 1] We experience the same problem on earth, although it can be very efficient in space. On earth, since we don't have a massive amount of gravitational energy to push the two atoms together, a high-temperature reaction system is required.[7] To date, the most power produced from a nuclear fusion reactor on earth was 16 MW while it expended 24 MW. With our current technology it is not feasible to replace other forms of energy on earth, however, it has been hypothesized that it could be achieved in space.[2]

Countries around the world have initiated programs to switch from fossil fuels to more renewable energy sources. Nuclear fusion reactors have been seen as the best long-term option for fuel production as Hydrogen could be generated from water.[8]

There are currently no fully operational nuclear fusion reactors. However, the International Thermonuclear Experimental Reactor (ITER), proposed at Geneva Superpower Summit in November 1985, began construction in 2017 in France and will begin producing plasma in 2025. It is estimated that by the

year 2035 it will be fully operational. The ITER will be capable of deuterium-tritium fusion. To put it in perspective, the fusion of one ton of deuterium-tritium mixture will produce the same amount of energy as burning 29 billion tons of coal. The energy produced would be in the form of heat which can then be harnessed into electricity.[2]

This source of energy production is interesting as it has the potential to both provide a clean energy source, but also incentivize innovation and space exploration. Helium-3, an even more efficient fuel type is found in abundance in the lunar regolith.

2. Body

In 1997, JET (Joint European Torus) set the record of 16 MW of power generated from a fusion reactor. However, in the process, it used 24 MW of power which applying that to eq. 2 gives a Q of 0.67.

ITER will use a deuterium-tritium reaction and is designed not only to reach the break-even point ($Q = 1$) but also to outperform it. It is expected to produce 500 MW of fusion power using only 50 MW of input power. When applied to eq. 2 produces a Q value of 10.

In order to generate the 50 MW of input power, three methods of heating will be used: Ohmic heating, Neutral Beam injection, and Cyclotron heating.

Ohmic heating occurs when an electric current is passed through a material. Neutral Beam Injection occurs when fast-moving particles are shot into the plasma and the resulting collisions lead to a transfer of energy into heat. Finally, Cyclotron heating uses radio waves to heat the plasma.

The biggest risk faced by the ITER will be the need to control the plasma. This will be achieved by producing a magnetic field around the plasma. Due to the fact that pressure could build inside a system like this one, ELM mitigation will be the process using smaller magnetic fields to punch small holes in the reactor's main field, reducing the internal pressure and therefore reducing the risk of plasma spurts.[2]

The nuclear fusion between deuterium and tritium forms Helium and energy, however it would also produce a neutron. Lone neutrons are hard to contain and result in a loss of energy.[10] The next problem is that tritium is very hard to come by and most of it is located in nuclear warheads. Helium-3 and a deuterium atom would be a much better alternative as instead of producing another neutron, a lone proton would be produced, which is significantly easier to contain resulting in much higher efficiency. To put it in perspective, a study in 1991 found that 25 tons of Helium-3 would be enough to power the entire United States for an entire year. The problem is that on earth, Helium-3 is very rare. In fact, it is believed that there is only 20,000 kg on earth. Helium-3 comes from solar winds which are blocked by the Earth's magnetic field. However, the moon has been bombarded by solar winds containing Helium-3. While the exact amount of Helium-3 is unknown, scientists speculate that there would be enough to power humanity for the next 10,000 years![9]

Both private companies and governments are striving for mining resources on the moon. One example is Google's Lunar-X prize for the best designed lunar mining system.[4] Arguments have also been made for extracting Helium-3 from Jupiter where it is even more abundant. However, due to our current technological abilities, it is likely that mining the moon will occur first and could spur a whole new industry.[5]

3. Economics of Mining Helium-3

In order to efficiently and effectively mine Helium-3 from lunar regolith, we would need to have a self-sustaining colony on the moon. Similar to the colonization of the new world 500 years ago, there would be three main steps. (i) Exploration (ii) Outpost (iii) Self-sustaining colony. The first stage has been completed by the Apollo missions and rover mapping of the lunar surface. Ignoring the politics, research from NASA has proposed that an outpost could be set up with our current technology for \$20 - \$40 billion dollars spread out over a decade. Scientists would begin testing many new technologies: production of rocket fuel from ice, growing food, mining Helium-3. At that point, private contractors would arrive looking to capitalize by manufacturing products cheaply and then shipping them back to earth.

Equation 3:

$$TCOE = E * p$$

Equation 4:

$$VPT = \frac{TCOE}{\frac{TCOE}{25(7.5 * 10^{10})}}$$

TCOE stands for the total cost of electricity, *E* stands for amount of energy used in kWh, *p* stands for the average price in dollars per kWh, and *VPT* stands for value per ton.

In 1991, Kulcinski performed an analysis of the value of Helium-3. He determined that 25 tonnes of Helium-3 could produce the same amount of energy required to last the United States a whole year.[12] In 2019, 4.13 trillion kWh of electricity was used while the average American paid 12 cents per kWh. If then we plug these figures into eq. 3, we get a value of \$495.6 billion. [14, 15] Using eq. 4 we find that a ton of Helium-3 would have a market value of \$3 billion.

Since 165.2 tonnes of Helium-3 could power 2019 United States for a year, now we have to talk about transport. The SPACEX Starship rocket will be our vehicle of choice. Although still unfinished, SPACEX has designed Starship with an earth to moon, or earth to mars payload capacity of 100 tonnes. As of now, SPACEX CEO Elon Musk speculates that a launch may be as low as \$2 million dollars, but will likely be between \$2 and \$10 million dollars, regardless, the launch cost would be negligible. Even though Starship may be able to lift more during a return trip from the moon as there is less gravity, resulting in a lower escape velocity, and it will be refueled onsite, we will keep a conservative cargo capacity estimate of 100 tonnes.[13] To put it in perspective, a Starship fully loaded with Helium-3 from the moon would have a market value of \$300 billion. Within two trips, Starship would have already brought back enough fuel to last the United States an entire year.

With nuclear fusion energy sources, it has been proposed that the price of electricity would be determined from the following formula:

Equation 5:

$$COE = \frac{C + DP}{E}$$

C is the annual operating cost, *DP* is the annual depreciation and *E* is the annual net electricity production. However, this ignores the price of building a nuclear fusion reactor, and how long it can be sustained, as this information isn't yet known.

The obvious current objection to this technology is that it is still under development and therefore is very expensive. As of 2018, the estimated cost of the ITER project was 25 billion dollars, more than double the original estimate. Nevertheless, since nuclear fusion reactions can't spiral out of control when something is going wrong like a nuclear fission chain reaction can, less safety equipment is needed, which is one of the largest costs of a nuclear fission plant. As a result, nuclear fusion reactors would be more cost-efficient in the long run as safety and cost are interconnected. Furthermore, in the spirit of looking for the most efficient and clean energy source, nothing else can rival nuclear fusion, especially fueled with Helium-3 as it is very efficient and produces no negative byproducts.[2]

4. Conclusion

Once the technology behind nuclear fusion becomes economically viable and behaves as promised, i.e., remaining efficient, safe, and clean, then power stations should begin to be replaced. Beginning with soon decommissioned plants, it would eventually grow into the most widely used source of electricity generation. If Helium-3 can be sourced reliably, nuclear fusion reactors should become the main source of fuel instead of the slightly radioactive tritium as it would lower risks of harming the reactor from excess neutrons, and not have the need for radioactive materials.[6]

For now, we will have to continue diversifying our electricity production sources until all these questions are answered: How much will a nuclear fusion power plant cost? How will electricity prices change around the world? Are there any unforeseen problems? Until then, we can't know the future of fusion energy, but we can be hopeful.

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