How three notable fusion energy companies are adapting to make fusion a reality

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ABSTRACT

The promise of fusion energy has garnered increased private and government funding. With this momentum, numerous startups have been trying novel approaches to achieve net energy gain, or getting more energy out than what was put in, within a realistic timeline. This review paper provides an understanding of some fundamental fusion reactor technologies – including tokamaks, field reversed configurations, and magnetized target fusion. Fusion startups have been adapting existing technology to achieve fusion by implementing novel approaches. This paper discusses the strategies taken by Commonwealth Fusion Systems (CFS), Helion Energy and General Fusion and sheds light on how these solutions are advancing the field of fusion reactors to make them commercially viable.

TABLE OF CONTENTS

1. Introduction

Energy usage is on the rise and meeting this demand in an environmentally friendly way is a challenging task. Experts agree that to meet global energy demands amidst a rapidly diminishing fossil fuel supply - coupled with the downsides to fossil fuel combustion - the reliance on fossil fuels must be reduced (Barbir et al., 1990; Smith et al., 2010). This is where nuclear fusion energy can play a key role. Nuclear fusion involves combining lighter atomic nuclei, most commonly deuterium and tritium, into heavier atomic nuclei and releasing energy in the process. Deuterium and tritium are hydrogen-like elements, i.e elements having one proton in their nucleus, that have one and two additional neutrons respectively as illustrated in Figure 1.

Fusion energy is a potential long-term alternative to fossil fuels as it provides a multitude of advantages, including but not limited to an abundant fuel supply, positive environmental impact by way of lower CO_2 emissions, and a lack of dangerous high-level nuclear waste as a byproduct (Anklam et al.,2011; Smith et al., 2010). A reduction in hazardous emissions can have a positive impact on agricultural initiatives by way of acid rain reduction, thus positively impacting food production (Barbir et al., 1990). Hazardous emissions can also have detrimental impacts on public water supplies and cause damage to urban infrastructure (Barbir et al., 1990).

The fusion energy landscape has changed considerably over the last few years. A whole host of startup companies have emerged and are actively pursuing novel approaches (Clynes, 2020). These developments have spurred interest towards this field and have led to an increase in private investment (Clynes, 2020). According to some estimates, the amount of private capital invested into fusion for the year 2021 was around 5 billion dollars (Hartwig, 2022). The same effect was observed in government funding as well, with a $107 million dollar increase in the federal budget for nuclear fusion endeavors in the year 2020 (Clynes,2020).

Experts have established a need to expedite the commercialisation of fusion energy as quickly as possible as it holds tremendous potential as a sustainable source of energy, however, the benefits to be gained in terms of CO_2 emissions and high-level nuclear waste avoidance diminish the longer it takes to commercialize fusion reactors (Anklam et al., 2011; Smith et al., 2010; The White House, 2022). Fusion researchers are experimenting with different approaches – new materials, different fuel mixtures, and different reactor technologies – to achieve net energy gain, or harvesting more energy from the reactor than the energy put in, and demonstrate commercial viability (Chatzis & Barbarino, 2021). Commercial viability, as of now, entails the resolution of specific challenges such as reactor and materials damage, fuel supply regulation, and the cost of building the reactor (Pearson, 2020). These are the obstacles that fusion startups such as Commonwealth Fusion Systems, Helion Energy, and General Fusion are racing to solve in the heat of fusion energy commercialization.

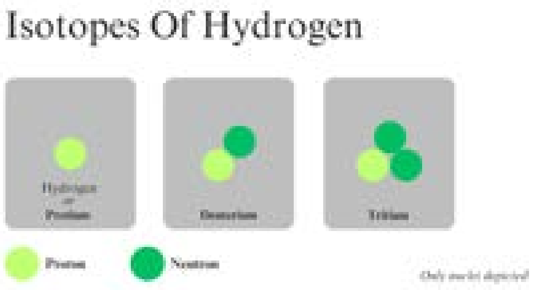

Figure 1. Nuclei of hydrogen isotopes

1.1 How does fusion energy work?

Nuclear fusion refers to the act of combining lighter atomic nuclei to form heavier atomic nuclei, releasing energy in the process. When two atomic nuclei are brought closer and closer, they tend to repel each other due to electrostatic repulsion, which refers to the force of repulsion between two charges with the same polarity. However, if these nuclei collide together so fiercely such that the strong nuclear force takes over, nuclear fusion takes place. The strong nuclear force is one of the four fundamental forces in the universe that is chiefly responsible for holding the particles of an atomic nucleus together. The strong nuclear force is stronger than the electromagnetic force (the force responsible for electrostatic repulsion) but it acts over shorter distances, thus the need to fiercely slam the nuclei into each other.

Nuclear fusion corresponds to a dip in the potential energy of the system. Additionally, the mass of the formed nucleus is always less than the sum of the masses of the nucleons, which is illustrated in Figure 2. This missing mass is called the mass defect, and this is what is responsible for the energy released during nuclear fusion (Diaz, 2023). The usual understanding of mass points towards mass always being conserved, however nuclear fusion is an exception and it uses Einstein's equation to relate energy and mass:

$$E = mc^2 \quad (1)$$

To understand the equivalency of mass and energy in the context of atomic nuclei, we use a slightly modified version of equation (1) to account for the masses of the particles that make up the nucleus. It is important to note that equations (1) and (2) are conveying the same idea.

$$\Delta E = (N_p * m_p + N_n * m_n - M_t)c^2 \; (2)$$

$\Delta E \ = \ The\ energy\ released\ after\ fusion$

$N_p \ = \ Number\ of\ protons$

$N_n \ = \ Number\ of\ neutrons$

$m_p \ = \ mass\ of\ a\ proton$

$m_n \ = \ mass\ of\ a\ neutron$

$M_t \ = \ mass\ of\ the\ final\ nucleus\ formed$

$c \ = \ Speed\ of\ light$

Nuclear fusion frequently takes place in astrophysical contexts in the cores of stars. The primary goal of nuclear fusion reactors is to emulate the high-temperature and high-pressure conditions needed to overcome repulsive forces and fuse atomic nuclei. A combination of deuterium and tritium is a favorable candidate as a fuel source for fusion reactors due to the fact that it can reach fusion conditions at lower temperatures than other alternatives and can release more energy (U.S Department Of Energy: Office Of Science, n.d.).

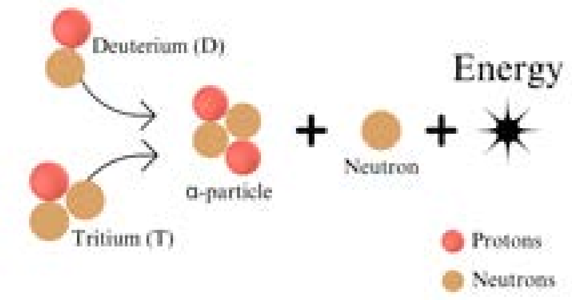

Figure 2. Deuterium-tritium fusion (DT-Fusion)

1.2 What is plasma and how is it related to fusion?

Plasma refers to a form of matter where electrons are separated from their nuclei. Fundamentally, a plasma is a sea of ionized particles that is approximately locally neutral. Just like solids can be melted down to liquids given sufficient energy, gases and solids can be supplied with enough energy to turn them into plasmas. However, unlike the other states of matter , the transition from a gas to a plasma does not have a well-defined temperature, instead it takes place gradually.

As outlined in section 1.2, when two atomic nuclei are brought closer and closer together, they must overcome an energy barrier due to electrostatic repulsion before the strong nuclear force takes over. In order to achieve fusion and overcome this barrier, the atoms must be heated to extremely high temperatures. At an atomic level, a higher temperature corresponds to a greater kinetic energy possessed by the particles, and this added kinetic energy allows them to be close enough to each other to allow fusion to take place. The temperatures required for fusion are large enough to strip atoms of their electrons. This means that for fusion reactors, the formation of plasma is inevitable.

1.3 Plasma confinement

Since nuclear fusion can only take place within a plasma, plasma confinement methods have been developed to maintain the temperatures and pressures necessary to sustain the fusion reaction and also to prevent the plasma from damaging the reactor due to the high temperatures involved. There are two main ways to confine a plasma: magnetic confinement and inertial confinement. Magnetic confinement fusion involves the use of strong magnetic fields to ensure that the charges within the plasma trace out helical trajectories along magnetic field lines (Sinha, 2023). Often, magnetic confinement fusion is characterized by the use of low density plasmas and high confinement times. Tokamaks , which will be discussed in section 2.1 , are a popular method of magnetic confinement fusion (Hartwig, 2022). Another plasma confinement technique is inertial confinement. Inertial confinement fusion is characterized by the use of a small fuel pellet that is compressed to fusion conditions most commonly using a large number of laser beams. However, these are not the only two confinement options available, a large number of modern fusion reactors have adapted techniques and principles from magnetic and inertial confinement fusion to give rise to novel methods of achieving fusion.

2. Reactor types

The primary objective of this section is to discuss the fundamental concepts and terms involved with three reactor designs: tokamaks, field reversed configurations and magnetised target fusion.

2.1 Tokamaks

Tokamaks are a category of nuclear fusion reactors that use strong magnetic fields to confine plasma within a vacuum vessel (essentially donut-shaped reactor vessels). Tokamaks are a very popular option for fusion reactors since they have shown promising results. All tokamaks can broadly be classified into two categories based on the aspect ratio, which is essentially measuring the ratio of a tokamaks width to its height as can be seen in figure 3 (Moser, 2023). A more formal definition of the aspect ratio is that it is the ratio of a tokamak's major radius to its minor radius (EUROFusion, n.d.). It is clear that the major radius is the distance from the center of the tokamak (the center of the "donut hole") to the center of the region where the plasma exists and that the minor radius is the distance from the center of the region of plasma to the reactor wall . Conventional tokamaks have an aspect ratio greater than 2.5 and spherical tokamaks have an aspect ratio anywhere between 1 and 2.5 (Moser, 2023). As can be seen from figure 4, conventional tokamaks generally have a height that is larger than their width, much like a torus, whereas spherical tokamaks tend to have heights that are similar to their widths, much like a sphere.

Figure 3. Aspect ratio of a tokamak

Figure 4. Conventional tokamaks and spherical tokamaks

Tokamaks use a combination of two different types of magnetic fields to confine plasmas. Figure 5 illustrates the magnetic field lines- those that go the long way around the torus constitute the toroidal magnetic field and the lines that go the short way around the torus constitute the poloidal magnetic field (Moser, 2023). When these two magnetic fields combine, they form a helical magnetic field that wraps itself around the entirety of the torus. To achieve this effect, tokamaks employ large magnets that produce strong magnetic fields. The helical magnetic field lines essentially trace out surfaces within the reactor to keep the plasma more effectively confined.

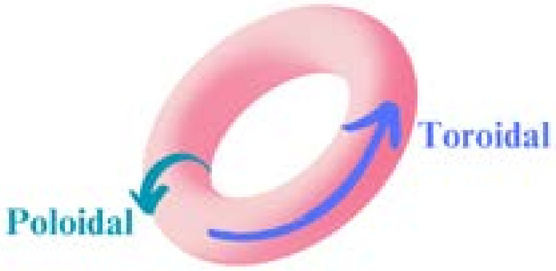

Figure 5. Poloidal and toroidal magnetic fields in a tokamak

Neutral gas added to the reactor chamber is first heated inductively using a process called ohmic startup where a central solenoid induces an electric field within the plasma to ionize it (Moser, 2023). The solenoid also drives an internal current within the plasma which generates a poloidal field (Moser, 2023). However, inductive heating is unsuitable for steady state operation due to inherent limitations (Moser, 2023). When an electric current is induced or generated in the plasma, the current faces resistance (a resistance to the flow of current) from the plasma due to collisions between particles, and this resistance is what heats the plasma initially (ITER ORGANIZATION, n.d.). This fact supplies one limitation of inductive heating - the resistance offered decreases as the temperature increases which means that the current's ability to provide further heating diminishes and therefore the overall heat produced by an inductive method is not enough to reach fusion conditions (ITER ORGANIZATION, n.d.). To counteract this, neutral beam injection is used, which involves positively-charged ions accelerated to high energies and then neutralized before being injected into the heart of the reactor such that they transfer their energy through collisions (ITER ORGANIZATION, n.d.; Moser, 2023). This drives currents within the plasma without the use of inductive methods, such as ohmic startup. Additionally it also heats the plasma non-inductively.

2.2 Field Reversed Configurations

Field reversed configurations (FRCs) fall into the category of compact toroids (Tuszewski, 1988). It is an alternative method of magnetic confinement fusion. An FRC is similar to a tokamak in terms of the shape of the plasma within the reactor. An FRC also employs a toroidal plasma, however, toroidal magnetic fields are not used to confine the plasma. Instead, an FRC employs poloidal magnetic fields only (Sutherland, 2023). The poloidal magnetic fields in an FRC are generated by a toroidal plasma current which is induced by an external magnetic field (Clynes, 2020). Essentially, current that flows the long way around the torus produces a magnetic field that makes its way along the short way around the torus. The direction of the axial magnetic field is reversed when compared to the external magnetic field (Clynes, 2020), which is shown in Figure 6. For a sustained FRC reactor, toroidal plasma currents need to be generated using methods such as neutral beam injection, which was discussed in the previous section. The plasma contained within an FRC can be divided into two separate regions based on how the magnetic field lines behave, as shown in figure 7. Within the reactor, there exists a boundary called the separatrix (Tuszewski, 1988). Inside the separatrix, the poloidal magnetic field lines are closed and they form loops around the plasma (Tuszewski, 1988). Outside the separatrix, the magnetic field lines are open and they do not resemble the tight loops that are seen within the boundary of the separatrix (Tuszewski, 1988). FRCs have certain advantages over other reactor designs. An FRC can achieve a similar plasma configuration as the tokamak without needing to use a central hole in the reactor , hence FRC's hold the potential to reduce the complexity of engineering the reactor (Clynes, 2020; Tuszewski, 1988).

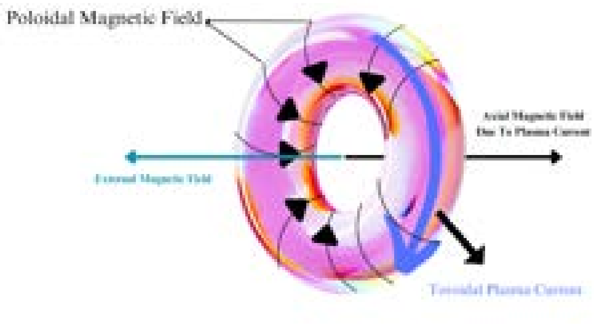

Figure 6. Magnetic fields and plasma current in a FRC

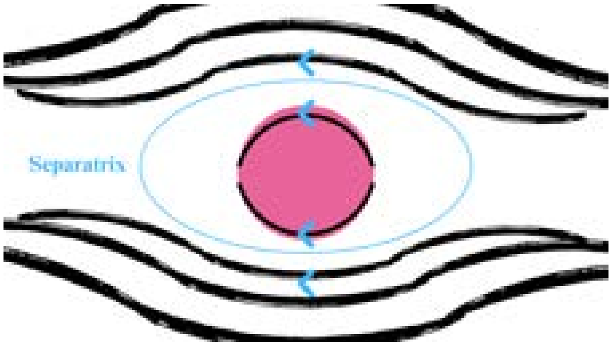

Figure 7. Separatrix of a field reversed configuration

2.3 Magnetised Target Fusion

Magnetised target fusion (MTF) combines confinement principles from both magnetic confinement fusion as well as inertial confinement fusion. This is why MTF is sometimes also referred to as magneto-inertial fusion. MTF uses magnetic fields to confine the plasma just like the tokamaks discussed in section 2.1 and the FRC's discussed in section 2.2 . However, MTF also employs principles from inertial confinement fusion to heat and compress the fuel to fusion conditions using lasers or pistons (Clynes, 2020).

MTF is attempting to implement the favorable aspects of both magnetic confinement and inertial confinement techniques (Wurden et al., 2015). MTF reaps the benefits of using higher density fuels and shorter confinement times, just like inertial confinement fusion, which produces a more stable plasma (Wurden et al., 2015). As for the principles adapted from magnetic confinement fusion, MTF uses an additional heating method from alpha particles, or the nuclei of helium atoms that are produced during the fusion reaction, which help in confining the plasma more effectively without losing energy too quickly (Thio & Francis, 2008; Wurden et al., 2015). Overall, MTF aims to adapt the best of magnetic confinement fusion as well as inertial confinement fusion.

3. Fusion Startups

This section will address the work being done by three notable fusion startups: Commonwealth Fusion System (CFS), Helion Energy and General Fusion. The reactor design, mode of operation and any notable achievements will be discussed in the following sections. The previous sections have served as the groundwork to effectively understand the work that is currently being carried out by these three companies.

To assess the approach taken by each of the startups, it is important to note a few key concepts. The first element in assessing any approach is the gain factor Q. The gain factor is expressed as follows

$Q = \text{Energy Output} / \text{Energy Input}$ (3)

A gain factor > 1 corresponds to net energy gain, which means that more energy is harvested from the fusion reaction than the energy that was put into the reactor. Another aspect to comparing any two approaches is the Lawson criterion. The Lawson criterion for breakeven is that the energy losses are balanced by both helium nuclei and neutrons, and the condition for ignition is that the energy losses are balanced solely by helium nuclei. The lawson criterion takes into account three factors, n, E , and T, which are the number of particles per unit volume, energy confinement time, and temperature of the plasma respectively. If for a given reactor, these parameters result in the value of Q as ≥ 0.1 , then the approach is a potentially viable method of achieving fusion (Hartwig, 2022). Another factor involved in analyzing a startup's approach is the choice of fuel. Considerations relating to the output energy and the probability of a reaction limit us to only a handful of viable options for fuels. D-T fusion is the most popular fuel used since it can undergo fusion at relatively lower temperatures than other fuels. However, D-^{3}He and D-D fusion are also viable options as a fuel (Hartwig, 2022).

3.1 Commonwealth Fusion Systems

Commonwealth Fusion Systems (CFS) is currently working alongside the Massachusetts Institute Of Technology (MIT) to develop a tokamak called the SPARC reactor (Chandler, 2021). MIT-CFS's SPARC reactor aims to solve a very specific problem with nuclear fusion reactors. As discussed in section 2, it is mandatory to confine the plasma in a nuclear fusion reactor with strong magnetic fields of some kind. This is common across all three of the fusion devices that have been discussed in section 2.

In tokamaks specifically, the strong magnetic fields are achieved using large superconducting magnets that surround the reactor vessel both poloidally and toroidally. MIT-CFS are actively working on a new type of high-temperature superconductor to be used as the source for the magnetic fields in their tokamaks. They have been able to successfully produce a strong magnetic field of 20 Tesla (T), making it one of the most powerful magnets on the planet. For context, a typical fridge magnet has a magnetic field strength of 0.01 T; thus the field strength of the CFS magnet is about 2000 times stronger than a typical fridge magnet (National High Magnetic Field Laboratory, 2022). To achieve this, they utilized 267 km of a ribbon-like tape made of the superconducting material. These ribbons are arranged as 16 stacked plates in a D-shaped housing. The primary advantage to this approach is that it allows the reactor to not only produce strong magnetic fields with less power but also to be able to produce more power in a smaller reactor (the major radius is 1.85m and the minor radius is 0.57m) (Henderson, n.d.). Additionally, because of the fact that the superconducting tape retains superconductivity at high temperatures, it can generate a stronger magnetic field. It is theorized that to emulate similar performance from other conventional tokamaks would mean operating an apparatus that is 40 times in volume. MIT-CFS's reactor is set to have a Q of greater than 10, or generating 10x as much energy on the output compared to the input.

Having a smaller reactor is beneficial due to reductions in cost of construction as well as prototyping(Commonwealth Fusion Systems, n.d.; Ferrell, 2021). However, the smaller size of the reactor means that the reactor is exposed to high thermal stresses due to the high power density, so the reactor's housing structure must be kept cold enough to manage the high temperatures, this is one of the primary challenges that the SPARC reactor will have to overcome (Ferrell, 2021). Overall, theoretical papers analyzing the reactor design and performance have confirmed that, given the magnets work as designed, the reactor should be able to reach its milestone of net energy gain (Chandler, 2021). The device is expected to produce about 50-100 MW (1MW = 10^6 W) of power. For context, a typical household lightbulb's power rating is about 60W, which means that the SPARC Reactor is expected to produce a minimum of about 800 thousand times more power than a lightbulb.

3.2 Helion Energy

Helion Energy is a startup based in Washington that is actively working on developing an FRC fusion reactor to make commercially viable fusion a reality. They have adapted principles from ion propulsion technology and implemented it in their reactor design. The reactor is composed of a large symmetrical tunnel-like structure that tapers towards the central section of the reactor, as shown in figure 8. The reactor consists of two formation sections where the toroidal plasma is generated to be used for fusion.

Helion energy uses a unique fuel mix of helium-3 and deuterium in place of the more conventional deuterium-tritium fuel mix. The rarity of tritium makes it a bottleneck to a viable fusion reactor due to the fact only 20 kilograms of it are available in global reserves (McManus, 2022). Traditional tokamaks are able to produce tritium by neutrons colliding with a neutron multiplier like beryllium and then implementing a blanket of lithium, but the use of beryllium drives up the cost of the reactor and also contributes to the production of radioactive nuclear waste due to neutron collisions with trace amounts of uranium present in beryllium (McManus, 2022). Helion's approach avoids this problem by means of their choice of fuel mix, deuterium and helium-3. Helium-3 is also extremely rare in nature but Helion has developed a patented method to produce helium-3 by means of deuterium-deuterium fusion reactions which do not have the aforementioned problems (McManus, 2022).

Initially the fusion fuel mix is injected into the reactor's formation section and subsequently ionized using electric fields as well as radiation. At this point the plasma is magnetically confined in order to prevent the reactor walls from being damaged. The fusion process begins with the formation of two toroidal rings of plasma on both ends of the reactor as described above. Then, by sequentially running high currents through the large coils that surround the reactor vessel , they accelerate the toroidal ring of plasma towards the central section of the reactor. The plasma makes its way to the reactor's plasma injector where the plasma is further accelerated to very high speeds while being compressed using strong magnetic fields (McManus, 2022). This compression heats the plasma and increases the pressure. In the central section of the reactor ,which is called the compression section, the two opposing plasma rings collide and come to a standstill (McManus, 2022). The high kinetic energy of the plasma heats it up even further until the plasma is ready to be fused (McManus, 2022). At this point the magnetic field strength in the central compression section is rapidly increased to produce fusion conditions and fusion starts to take place (McManus, 2022). This is where Helion Energy has implemented another unique piece of technology.

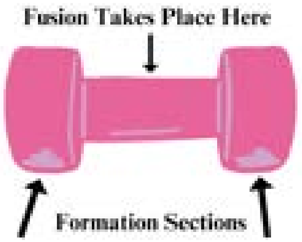

Figure 8. Helion Energy's fusion reactor shape

While traditional fusion reactors use the heat generated from the fusion reaction to run steam turbines to produce electricity, Helion Energy has used a novel approach known as direct energy conversion (Ferrell, 2022). Essentially, when fusion begins to take place, the fuel mix expands to push back on the magnetic field that confines it. This changing magnetic field can be used to drive currents in external copper wires without the use of any intermediate infrastructure such as steam turbines. This phenomenon is governed by a particular law in physics that is referred to as Lenz's law, which can be written as follows

$$\epsilon_{ind} = \oint \vec{E} . d\vec{l} = -\frac{d\phi_B}{dt} \qquad (4)$$

$\vec{E} = Electric\ field\ vector$

$\epsilon_{ind} = Induced\ electromotive\ force\ or\ induced\ voltage\ in\ the\ conducting\ loop$

$d\vec{l} = Infinitesimal\ length\ vector\ along\ the\ current\ direction\ in\ the\ conducting\ loop$

$\phi_B = Magnetic\ flux\ experienced\ by\ the\ conducting\ loop$

This law states that when the magnetic field around the conducting loop changes, current is produced in the loop which itself produces a magnetic field in such a way so as to oppose the change that gave rise to it. In Helion's case, the magnetic field changes around a copper conducting loop due to the fact that the plasma pushes back on the high intensity magnetic field that confines it (McManus, 2022). This produces current in the loop that can be directly harnessed without the use of turbines (McManus, 2022). The key takeaways here are the benefits that this method confers to the reactor.

Apart from contributing to the efficiency of energy recovery, this method of energy conversion eliminates the need for the fusion fuel to achieve ignition, which is when the fusion reaction is self-sustained (Ferrell, 2022). This simple but effective adaptation may possibly be able to eliminate any potential obstacles in the way of a viable fusion reactor. Additionally, the smaller size of the reactor will reduce the costs involved in developing and prototyping such a reactor (ARPA-E, n.d.).

As for the future of the company, the company's sixth generation reactor named “Trenta” is currently operational and they're actively working on the seventh generation “Polaris” along with running simulations of their eighth generation machine (Ferrell, 2022). By parallelly developing multiple reactors, the company is able to rapidly learn from past mistakes and accelerate the development of a commercially viable reactor (Ferrell, 2022).

3.3 General Fusion

The Canadian startup General Fusion is employing a fusion reactor that works on the principle of magnetized target fusion, which has been covered in section 2.3. General Fusion' primary goal is to make a viable fusion reactor for the market by 2030 (Ferrell, 2022). General Fusion's reactor chamber consists of a rotating liquid vortex composed of molten lead and lithium that is kept securely in place with the help of a spinning rotor. The reactor employs a magnetically confined plasma for its fusion reactions. The chamber is surrounded by a large number of steam-driven pistons that are responsible for actually compressing the fuel mix (Ferrell, 2022). The pistons , which are moved at varying rates, generate shockwaves through the molten metal towards the center of the reactor (Patel, 2021). These shockwaves are what cause a fusion reaction to take place upon compression of the plasma (Patel, 2021). The heat generated in the fusion reactor is conducted by the metal and then is ultimately used to drive a steam turbine that produces usable electricity (Ferrell, 2022). It is important to note that the neutrons generated during the reaction are responsible for providing heat to the metal (Patel, 2021). This reactor, much like helion's reactor, is a pulsed system, with the compression system activating once a second (Patel, 2021).

General Fusion's reactor design's simplicity is what they're banking on to materialize a commercially viable reactor. For starters, the company's reactor employs copper electromagnets in place of cryogenically cooled superconductors, thus simplifying the design and lowering the costs involved (Patel, 2021). Additionally, the company is leveraging advances in machine learning and advancements in computer simulation technology to their advantage (Ferrell, 2022). To be more specific, the company is implementing fluid simulations to understand the behavior of the liquid vortex under compression (Ferrell, 2022). This knowledge will be helpful in expediting the development of a commercially viable reactor.

The liquid vortex in and of itself is advantageous to the overall reactor design in more than one way. For reactors employing fusion fuel mixes that produce neutrons upon achieving fusion, the reactor walls undergo degradation of the lifetime of the reactor (Clynes, 2020). This is why they need to be replaced frequently since they are considered to be low-level nuclear waste (Clynes, 2020). This is where General Fusion's reactor design is advantageous. The liquid metal vortex essentially acts as a shield to the incoming neutron radiation and protects the reactor walls (Patel, 2021). That being said, this system is not perfect by any means. The liquid metal itself is irradiated to some degree (Clynes, 2020). However, the need to regularly replace the liquid metal is eliminated and therefore the reactor solves the issue of constantly producing low-level nuclear waste (Clynes, 2020).

As of 2021, the company has run over 200,000 experiments on a one-tenth scale model (Patel, 2021). The company is currently working on developing a fusion demonstration plant in the UK in partnership with the Culham Centre for Fusion Energy (Ferrell, 2022). The company claims that the demonstration power plant will be up and running by 2025 and the full scale commercial plant is expected to be operational by approximately 2030 (Patel, 2021). The experiments have helped them test the individual components that will comprise the demonstration plant. The demonstration plant , if successful, will provide insights into the viability of the planned full scale reactor (Patel, 2021). Alongside these efforts, preparations are being made for the full scale reactor, with the company looking for a suitable location for the full scale reactor (Patel, 2021).

Conclusions

This paper discusses the fundamental concepts behind nuclear fusion reactors and analyzes three notable fusion startups along with the physics of the reactor designs they employ. Overall, a rise in private funding has been met with a rise in the number of fusion startups looking to develop a commercially viable fusion reactor that can sustainably produce electricity and reduce our dependence on fossil fuels. Commonwealth Fusion System's fusion reactor adapts tokamak technology by implementing high-temperature superconducting magnet technology to scale down the reactor and reduce the cost of prototyping the reactor. Helion Energy's reactor design adapts conventional FRC technology with a novel fuel mix and an efficient method of energy conversion. General fusion's reactor design adapts MTF technology by leveraging advancements in technology, implementing a liquid vortex to protect the reactor walls, and using inexpensive magnets to confine the plasma.

Overall, fusion energy is clean, abundant energy for the masses. Additionally, climate change aside, having access to an abundant source of energy could be the key to solving major issues relating to energy access, food security, and water contamination.

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