The possibility of the commercialization of fusion energy

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How can fusion reactors be optimized to maximize efficiency and effectiveness in harnessing usable energy?

Abstract

Nuclear fusion is considered by many to be the holy grail of energy production, harnessing the same source of energy that fuels the stars. It could give us a source of clean and sustainable source of energy, eliminating the need for fossil fuels. Fusion energy is a sustainable, environmentally clean power source using isotopes of hydrogen and sometimes helium as its fuel. The fusion process produces no greenhouse gasses or long-lived radioactive waste materials and ensures energy security for the long term. This paper will look into 3 methods of obtaining fusion, inertial confinement fusion, magnetic confinement fusion, and magneto-inertial fusion, and their respective methods of harnessing energy and how thermal transfers can be optimized to increase energy output.

1 Introduction

Fossil fuels are the largest contributor to climate change, causing 75% of all greenhouse gases and 90% of global carbon dioxide emissions. For the past 150 years, our society has relied heavily on fossil fuels for our energy production. As of 2021, the United States relied predominantly on petroleum for energy, making up 36.0% of its energy, followed closely behind by natural gases at 32.2% and coal at 10.8%. (EESI, 2023) Although fossil fuels have shown to be dependable and abundant, fossil fuels, when extracted and used, have many negative impacts on the environment and human health. The burning of fossil fuels releases harmful pollutants into the air, contributing to climate change and global warming. Furthermore, fossil fuels are nonrenewable meaning that the use of fossil fuels depletes natural resources that can't be easily produced again.

To address these issues and ensure a cleaner, safer future, many governments and associations are encouraging the use of more sustainable alternatives to fossil fuels. One of these alternatives is the use of nuclear energy, specifically the use of fusion reactors.

2 Fusion Energy

Nuclear fusion, unlike its counterpart fission which generates energy through the process in which large nuclei such as uranium-235 or plutonium-239 get broken into smaller nuclei when absorbing an extra neutron, generates energy through the process of fusing 2 or more atomic nuclei together to form a larger nucleus and nucleons. This process generally releases a large amount of energy, however, if the fusion process produces an atomic nuclei heavier than iron-56 or nickel-62, the fusion reaction will not release energy and instead will require energy. This is due to the fact that at a certain point, the potential barrier that the particles must overcome is significantly larger than the amount of energy that is released from the process.

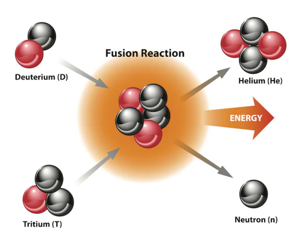

Figure 1: Fusion process (Shutterstock, 2024)

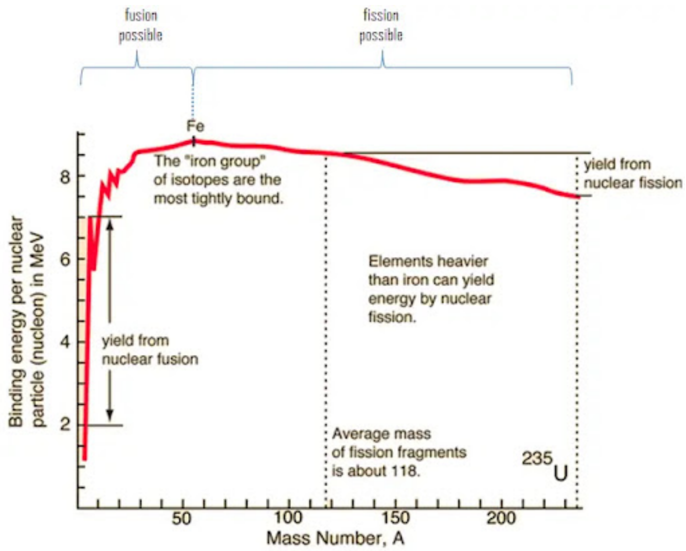

Figure 2: Binding energy of different atomic nuclei (Labman, 2024)

Nuclear fusion is considered the holy grail of energy production due to it having the potential to provide an almost limitless source of energy while also being sustainable (Clifford, 2022). All stars in our universe use nuclear fusion to generate energy and keep burning. Nuclear fusion can be powered by hydrogen isotopes, which are widely available and produce relatively little radioactive waste, as opposed to nuclear fission, which has a side product as radioactive waste and uses many rare radioactive elements.

However, despite decades of testing and research, widespread use of fusion still remains a challenge due to the many requirements that two nuclei need to undergo fusion, such as the incredibly high temperatures needed for fusion to occur and the difficulty in effectively harnessing the energy from these reactions. The most advanced fusion experiments are being conducted in large international projects, such as the International Thermonuclear Experimental Reactor (ITER) which is an international fusion research and engineering project currently being built in France. The purpose of these projects is to show that fusion energy is feasible and to develop the necessary technologies needed to construct a commercial fusion power plant. The most developed and advanced fusion devices mostly use either inertial confinement or magnetic confinement for their methods of producing fusion. There is also a third, less developed method, known as magneto-inertial fusion which has also been able to deliver net energy gain.

2.1 Fusion requirements

For fusion to occur, the atomic nuclei need to be heated to extremely high temperatures, at least 100,000,000°C, to overcome the electromagnetic repulsion and fuse. The Coulomb barrier (Birtannica, 2024), named after physicist Charles-Augustin de Coulomb, is the energy barrier due to the electrostatic repulsion that two nuclei need to overcome so that they can get close enough to undergo a nuclear reaction. The energy barrier is given by the electric potential energy:

$$U_{coul} = k\frac{q_1 q_2}{r} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r}$$

where

k is the Coulomb constant $= 8.9876 \times 10^9 Nm^2C^{-2}$
ϵ_0 is the permittivity of free space
q_1, q_2 are the charges of the interacting particles
r is the interaction radius

A positive value of U is due to a repulsive force, so interacting particles are at higher energy levels as they get closer. A negative potential energy indicates a bound state (due to an attractive force).

$$U_{coul} = \frac{kZ_1Z_2e^2}{r}$$

where e is the elementary charge, $1.602176634 \times 10^{-19}C$, and Z_i the corresponding atomic numbers.

To overcome this barrier, nuclei need to have high kinetic energy so that they can overcome the electrostatic repulsion and get close enough for the strong nuclear force to take place and bind the nuclei. However, sometimes, if two nuclei can be brought close enough together, the electrostatic repulsion can be overcome by quantum tunneling where the nuclei can tunnel through coulomb forces. (Hyperphysics, 2024)

The binding energy as a net result of the opposing electrostatic and strong nuclear forces per nucleon will increase with increasing size, up until elements Iron and Nickel, where the binding force decreases until eventually, at over 208 nucleons (approximately a diameter of 6 nucleons), atoms become unstable. An outlier to this trend is Helium-4, which due to the Pauli exclusion principle that states that fermions cannot exist in the same nucleus in the same state, each of the two protons and neutrons can be in the ground state, causing the binding energy to be higher than Lithium. Any additional nucleons would have to go into higher energy states.

The Coulomb barrier is the smallest for isotopes of hydrogen due to only having a single positive charge. This makes it an ideal choice for nuclear fusion. A diproton is unstable, meaning that neutrons need to be involved, ideally in such a way that a helium-4 nucleus, with its extremely tight binding, is one of the products. If we try using deuterium-tritium fuel, the Coulomb barrier will be around 0.1 MeV. The result of the fusion (He^5) is unstable. The He^5 nucleus immediately will eject a neutron with 14.1 MeV. The recoil energy of the He^4 is 3.5 MeV. This gives us a total energy of 17.6 MeV. This is many times more than how much energy was needed to overcome the energy barrier.

The reaction cross section (σ) is a measure of the probability of a fusion reaction as a function of the relative velocities of the 2 nuclei. If the reactants have a thermal distribution, an average of the distributions of the product of cross section and velocity should be taken. This average is known as the reactivity, denoted $\langle\sigma v\rangle$. The reaction rate (fusions per volume per time) is $\langle\sigma v\rangle$ times the product of the reactant number densities. The reactivity $\langle\sigma v\rangle$ increases from virtually zero at room temperature to meaningful magnitudes at temperatures of 10 - 100 KeV (1 KeV = 11.6 million Kelvin). At these temperatures, well above typical ionization energies (13.6 eV for hydrogen), the fusion reactants exist in a plasma state.

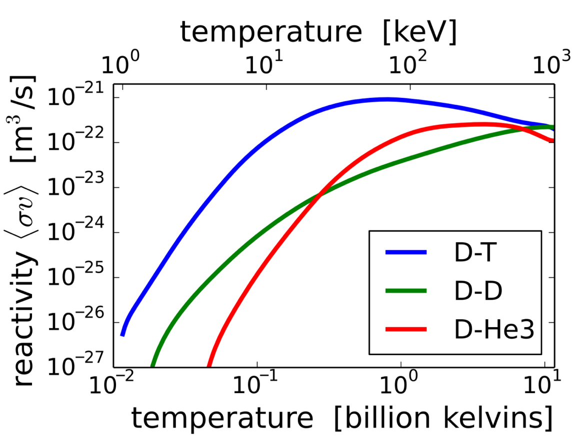

Figure 3: Reactivity of common fusion reactants (Wikipedia, 2024)

At low temperatures, the reactants won't have enough energy to overcome the electrostatic repulsion to get close enough to interact with the strong force. However, if the temperature is too high then the reactants will have so much energy that the strong force will not be able to bind them together. Additionally, the collisions at high temperatures will break apart the nuclei before they can be formed. This means each combination of reactants has an ideal temperature for fusion.

We know that the sun only reaches a maximum of 15,000,000°C which is much less than the 100,000,000°C that is the temperature at which a significant amount of the plasma can undergo fusion yet we know that the sun's core fuses hydrogen. On Earth, we are only able to confine small amounts of low-density plasma at once, meaning to get a net energy gain, we will need most of it to fuse. On the other hand, the sun has no problem confining large amounts of plasma due to its strong gravity. To keep itself burning, only a small portion of the total plasma needs to fuse. This still however isn't enough fusion to keep the sun burning so the nuclei will quantum tunnel through the energy barrier. It rarely happens but it's enough to keep the sun burning at such a low temperature.

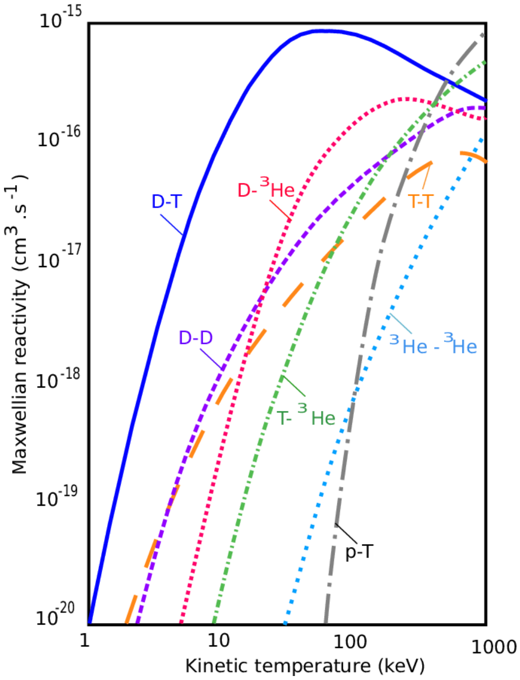

Figure 4: Reactivity for other fusion reactants (Bahmani, 2024)

2.2 Issues with fusion

One of the major issues fusion faces is containing the plasma that's used in the fusion process. For optimal fusion, the plasma in fusion reactors reaches temperatures of over 100 million degrees Celsius, hotter than the core of the sun. At these extreme temperatures, no physical material can directly contain the plasma. This means that many developments need to be made to contain this extremely high-temperature plasma that is needed to give the atomic nuclei enough kinetic energy to fuse.

Another major issue that fusion energy faces is efficiently extracting the thermal energy produced by fusion reactions and converting it into electricity. In most fusion power plants, the heat generated by fusion reactions is captured and used to drive turbines or other generators. Developing materials and systems that can withstand the neutron bombardment and extreme temperatures involved is a significant engineering challenge. Materials must not only be resilient but also efficient in conducting thermal energy to minimize energy loss.

For some fusion reactor designs that involve aneutronic fuels, fuels that don't result in neutrons, direct energy conversion is possible. These methods aim to convert the kinetic energy of the fusion products directly into electrical energy, potentially offering higher efficiency than traditional heat exchange mechanisms as they don't need an intermediate material to absorb the thermal energy. However, developing practical, efficient direct conversion technologies is complex and requires overcoming significant scientific and engineering obstacles.

Furthermore, the high temperatures and neutron flux in a fusion reactor can lead to thermal stress and fatigue in the reactor's structural materials. Over time, this can cause cracking, material degradation, and even failure, posing significant challenges to the durability and longevity of fusion reactors. Finding workarounds to minimize these stresses will be necessary in having reliable and efficient operational fusion power plants.

3 Magnetic confinement fusion

Magnetic Confinement Fusion (MCF) is one of the most promising approaches to achieving controlled nuclear fusion reactions on Earth. It involves using strong magnetic fields to confine and control the plasma, meaning the plasma never needs to interact with the fusion chamber's walls. The most common devices that use magnetic confinement fusion research are tokamaks and stellarators. (Kiger & Freudenrich, 2021)

Some of the most advanced fusion research and experiments are done at the International Thermonuclear Experimental Reactor (ITER) in France which uses a tokamak design. The design uses a large array of superconducting magnets to contain the plasma upwards of 150 million degrees Celsius.

It started construction in 2010 and is, as of December 31st 2022, 77.5% complete. Members of ITER include China, the European Union, India, Japan, South Korea, Russia and the United States. The ITER project had an initial project budget of €6 billion. However, the total price of construction and operations is projected to be from €18 to €22 billion, other estimates place the total cost between $45 billion and $65 billion, though these figures are disputed by ITER. (IAEA, 2021)

ITER consists of 39 buildings that house the ITER Tokamak reactor and its systems. In the center of the facility is the Tokamak building which holds that actual reactor.

Figure 5: ITER Tokamak site (ITER, 2024a)

The reactor starts by pumping out any air or impurities from the vacuum chamber. The gaseous fuel is then introduced to the chamber and the magnetic systems are charged up. An electric current is passed through the reactor, breaking down and ionizing the gas so that the electrons are stripped away from the nuclei, forming a plasma. Auxiliary heating systems increase the temperature to 150-200 million°C, causing the plasma particles to collide and fuse together, releasing large amounts of energy. (ITER, 2024b) (TWI, 2024)

Tokamak reactors harness the energy of fusion by absorbing the energy into the walls of the reactor. The plant then takes this thermal energy to produce steam, driving turbines that generate electricity. Tokamak reactors use torus-shaped vacuum chambers where inside, hydrogen is subjected to extreme heat and pressure until it becomes plasma.

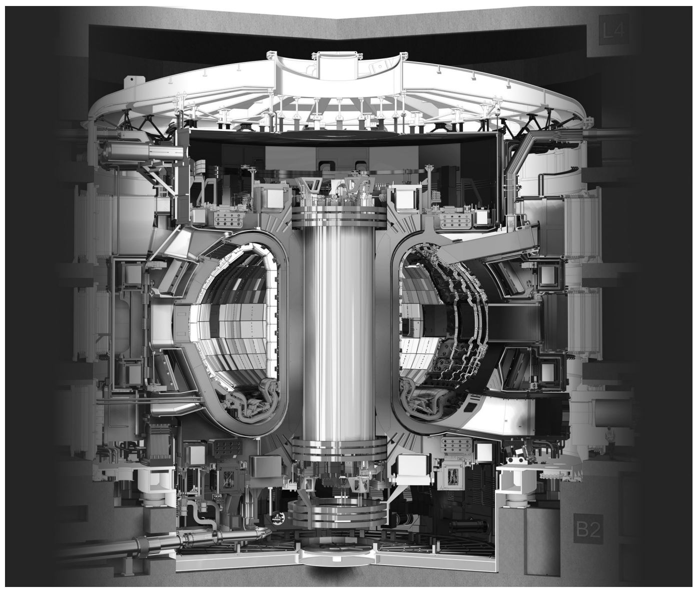

Figure 6: ITER Tokamak (ITER, 2024a)

3.1 Fuel

The fusion reaction in the ITER reactor will be powered with deuterium and tritium, producing helium-4 and a neutron. Powerful custom-made pumps inject the gaseous fusion fuels into the vacuum chamber at an average of 200 Pa$\frac{m^3}{s}$. Less than 1g of fuel will be present in the vacuum vessel at any one moment. The diverter located at the bottom of the vacuum vessel recycles any fuel not consumed, separating it from the helium produced from the fusion reaction, mixing it with fresh tritium and deuterium, and then injecting it back into the vacuum chamber. (ITER, 2024a)

However, tritium is a rare isotope of hydrogen, with an estimated 20kg of it in global reserves. A single commercial-scale tokamak is expected to use around 300g of tritium each day, giving an estimated 2 months of operation with the world's entire current supply. ITER plans to use a lithium breeding blanket within the reactor to make its own tritium as when the lithium is hit by the high-energy neutrons, it splits into helium-4 and tritium. However, the neutrons carry around 80% of the fusion's energy, meaning that most of the energy is now lost. To combat this, tokamak walls are made of beryllium, acting essentially as a neutron multiplying as when hit by a neutron, it splits into 2 helium-4 atoms and 2 neutrons. However, beryllium is very expensive. The entire global annual supply of beryllium is just enough to make a single tokamak reactor.

3.2 Fusion containment

ITER uses custom-built Niobium-Tin superconducting magnets in their Tokamak reactor to contain the plasma. These superconducting magnets must run at 4K (-269°C) to run effectively with a total of 100,000km worth of superconducting strands. The reactor has 6 main components to its magnet system, all used for different purposes to aid in controlling the plasma within the chamber: the toroidal field system, the poloidal field system, the central solenoid, correction coils, in-vessel coils, and magnet feeders. The toroidal and poloidal field systems are used in conjunction to shape and confine the plasma, keeping the plasma away from the walls of the chamber. These magnets can produce upwards of 12 tesla, outputting a total magnetic energy of 45 gigajoules. The most powerful magnet in the system, the central solenoid, is the backbone of ITER's magnet system, allowing for a powerful current to be induced in the plasma and maintained for long periods. There are additionally 18 smaller superconducting correction coils inserted between the toroidal and poloidal coils to compensate for field errors created by geometric deviations in manufacturing and assembly. 2 non-superconducting coil systems are located within the plasma chamber to provide additional control over the plasma. These magnets provide vertical stabilization of the plasma as well as create resonant magnetic perturbations in the plasma so that edge-localized modes (ELMs) are avoided. Finally, the magnet feeders deliver the required power and cryogenic fluids to cool and control the temperature of the magnets. (ITER, 2024b)

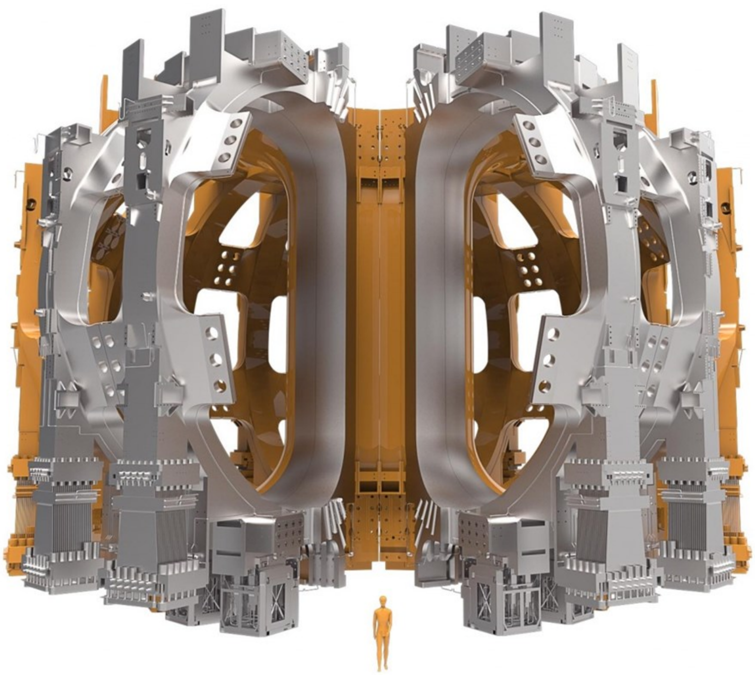

Figure 7: Toroidal field magnets (ITER, 2024a)

3.3 Energy harnessing

The fusion takes place in a component known as the vacuum vessel. When the neutrally charged neutrons created from the fusion process escape the magnetic field, they are absorbed by blanket modules. As the blanket absorbs energy from the fusion reactions, its energy is converted into heat energy and is collected by water coolant. This water then runs a turbine, generating electricity. Neutron radiation is mitigated by in-wall shielding made of borated and ferromagnetic stainless steel. These modular blocks provide shielding from neutron radiation to components located outside of the vacuum vessel and also contribute to plasma performance by limiting toroidal field ripples.

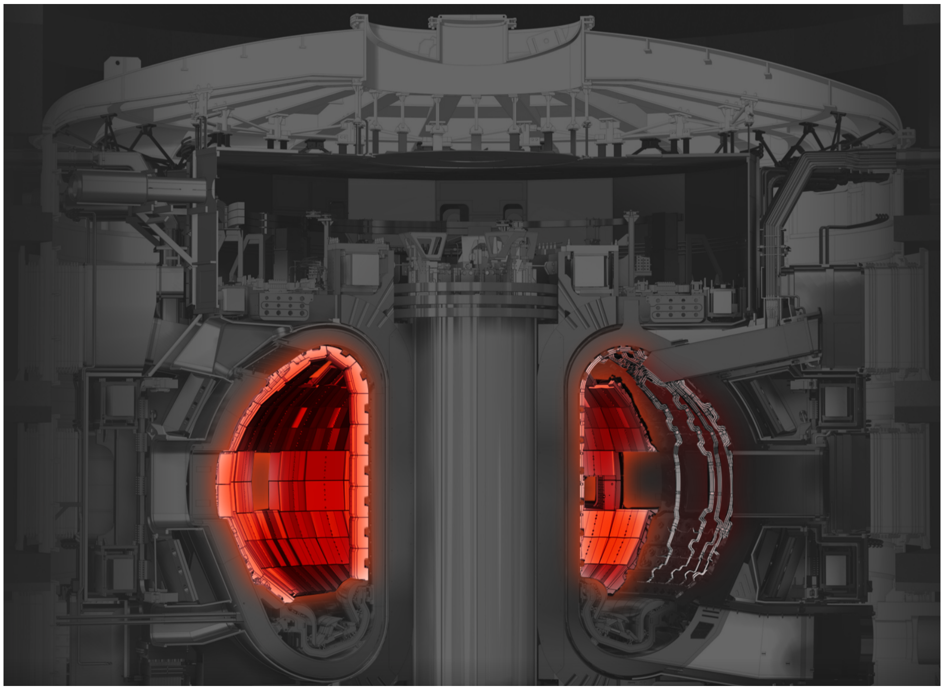

Figure 8: Blanket modules (ITER, 2024a)

3.4 Advantages of magnetic confinement fusion

Magnetic Confinement Fusion devices, such as tokamaks and stellarators, are designed for continuous operation, where plasma is sustained for extended periods. This differs from inertial confinement fusion which can only run in pulses. This steady-state operation allows for stable and predictable energy production, similar to conventional power plants.

Additionally, magnetic confinement devices are scalable, allowing for the construction of larger reactors to increase power output. This scalability makes MCF ideal for power generation on a commercial scale, with the potential to meet significant energy demands.

The magnetic fields used in MCF devices provide stability to the plasma, eliminating instabilities and turbulence that could disrupt fusion reactions. By carefully controlling the configuration and strength of the magnetic fields, researchers can suppress instabilities such as disruptions and edge-localized modes (ELMs). Furthermore, advancements in plasma control techniques, such as active feedback control systems or AI techniques, allow for real-time adjustments to maintain plasma stability.

Magnetic confinement also allows for efficient control of heat and particle exhaust from the plasma. In tokamaks, for example, magnetic fields shape the plasma and guide it along predetermined paths, facilitating controlled exhaust mechanisms. This enables the removal of impurities and excess heat from the plasma while maintaining optimal conditions for sustained fusion reactions.

3.5 Disadvantages of magnetic confinement fusion

The systems that maintain the magnetic fields in MCFs require complex computations and calculations to achieve and maintain plasma stability. Plasma instabilities such as disruptions and edge-localized modes (ELMs) can lead to sudden loss of confinement and damage to the reactor walls. These plasma instabilities can cause energy losses, decreasing efficiency.

Since MCFs are made to be run for extended periods of time, efficiently removing heat and particles from the plasma is crucial for sustaining the reaction. This involves developing techniques for managing plasma exhaust and maintaining optimal conditions for fusion. Furthermore, The extended use of these devices can cause erosion and damage to the tokamak's internal components over time. Developing materials that can withstand these harsh conditions is essential for the long-term operation of tokamak reactors.

MCF reactors tend to be larger and more expensive than systems that utilize inertial confinement. Tokamaks, for example, often require massive superconducting magnets and extensive infrastructure to contain and control the plasma, making them costly to build and maintain.

Additionally, MCF reactors require a lot of energy to be spent on cooling the superconducting magnets to near absolute zero for optimal operation. This is made worse by the fact that there is plasma heated to 150,000,000°C right next to these magnets. These cryogenic systems can use up to 80% of total energy output, making these systems inefficient.

In MCF reactors typically produce large numbers of high-energy neutrons, which can activate reactor components and induce radioactivity. Managing neutron-induced activation and radiation shielding requirements adds complexity and cost to MCF reactor designs.

MCFs primarily use deuterium and tritium as fusion fuels. Tritium, in particular, is a scarce resource, with an estimated of 7.3kgs in Earth's entire reserve. This means using tritium will require breeding within the reactor or external production facilities. This can add to the complexities and costs of the fusion reactor.

4 Inertial confinement fusion

Inertial Confinement Fusion (ICF) is another option to confined fusion many have pursued to achieve controlled nuclear fusion. ICF initiates nuclear fusion reactions by compressing and heating targets, typically small pellets containing deuterium and tritium. ICF works by depositing energy into the shell of the pellet which then explodes inwards, triggering fusion within the pellet. (Laboratory, 2022)

Figure 9: NIF site (Cartlidge, 2022)

The largest operational ICF experiment is the National Ignition Facility (NIF) in the US which has shown ICF can produce net energy gain, producing 1.5 times the energy that was delivered to the pellet. The design uses 192 lasers to compress and heat the pellets to the necessary temperatures. (Laboratory, 2022)

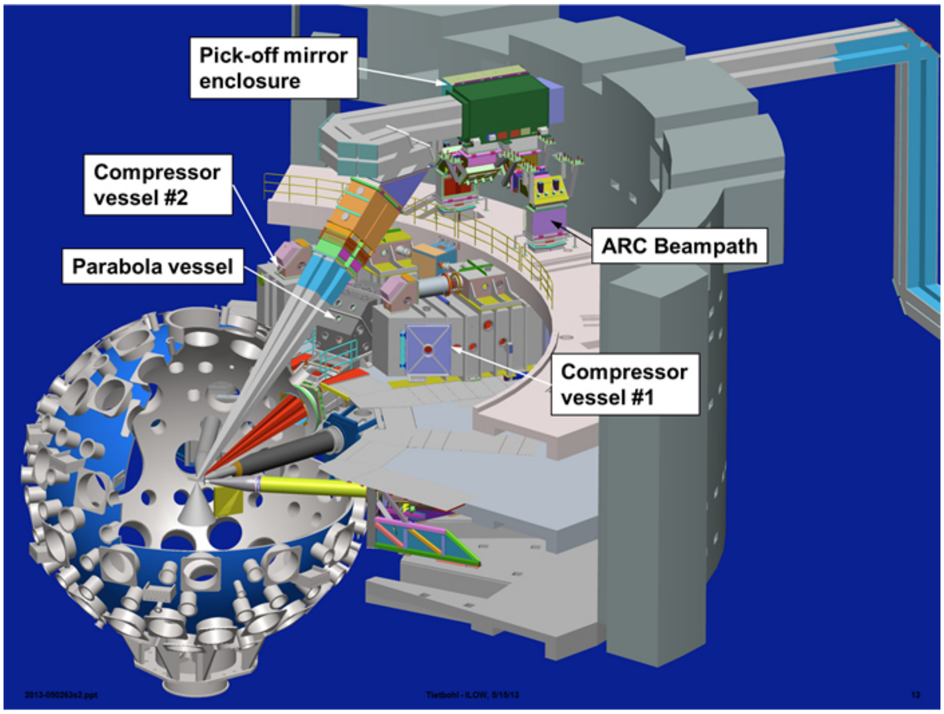

Figure 10: Inertial confinement fusion system overview (Laboratory, 2022)

The fuel pellet, typically a sphere, contains a mixture of deuterium and tritium. The fuel pellet is then compressed and energy is transferred to the pellet to increase the kinetic energy of the particles. The fuel pellet is compressed to a fraction of its original size, increasing its density and temperature to the point where nuclear fusion can occur. This is typically done using one of two methods:

- Laser-Based ICF: High-energy lasers are focused on the surface of the fuel pellet from all directions, uniformly heating the outer layer of the pellet. The outer layer explodes outward, creating a reaction force that compresses the inner part of the pellet to extremely high densities and temperatures.
- Heavy Ion or Particle Beams: Alternatively, particle beams (like heavy ions or electrons) are sometimes used to compress and heat the fuel pellet.

As the pellet compresses, it also heats up. The pellet reaches temperatures exceeding 100,000,000°C, at which point the kinetic energy of the nuclei is high enough to overcome their electrostatic repulsion. The energy of the neutron from the fusion reactions is then captured in a surrounding blanket material, where its energy is transformed into heat. This heat can then be used to produce steam and drive turbines, generating electricity in a process similar to conventional power plants.

4.1 Fuel

The fuel used in ICF reactors is contained within a capsule known as a hohlraum, a cavity whose walls are in radiative equilibrium with the radiant energy within the cavity. The hohlraum body is usually made of an element with a high atomic number, such as gold or uranium. Inside the capsule is a mixture of deuterium and tritium fuel. To ignite the capsule, a radioactive source, such as an array of lasers, is pointed at the interior of the hohlraum causing the inner portion of the fuel capsule to implode and supercompressing the D-T fuel, activating a fusion reaction. In an indirect drive system, the hohlraum wall will also absorb and reradiate this energy as X-rays, forcing more energy into the fuel. In a direct drive system, the fuel is compressed only by the radiative source, most commonly lasers. (Lind, 2022) (Laboratory, 2022)

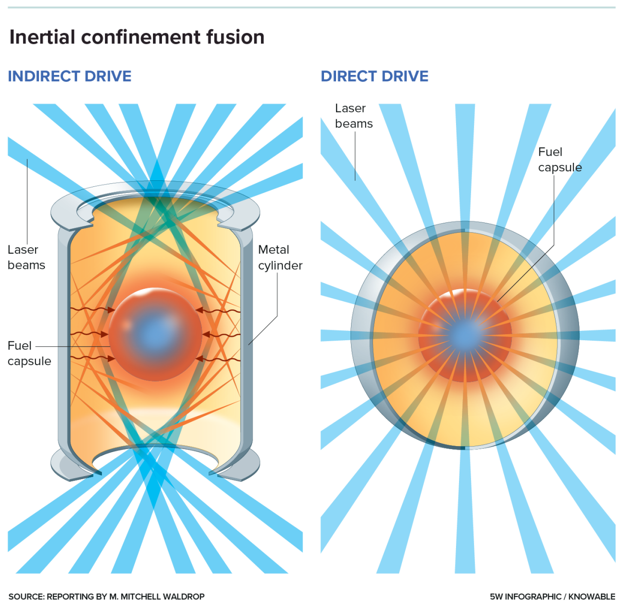

Figure 11: Hohlraum indirect vs direct drive (Waldrop, 2024)

4.2 Fusion containment

The fusion that occurs in ICF reactors is contained by the large arrays of lasers that are used to compress the fuel pellet. The NIF reactor at the Lawrence Livermore National Laboratory uses an array of 192 lasers to compress and heat the fuel pellet. The 192 laser array starts off as a single weak laser pulse that is then split into 48 beams each going into its own preamplifier that increases the pulse's energy by a factor of 10 billion. The 48 beams are then split into four more beams each for injection into the 192 main laser amplifier beamlines. When the laser beams finally reach the target, they each have over 2 million joules of ultraviolet. (Laboratory, 2022)

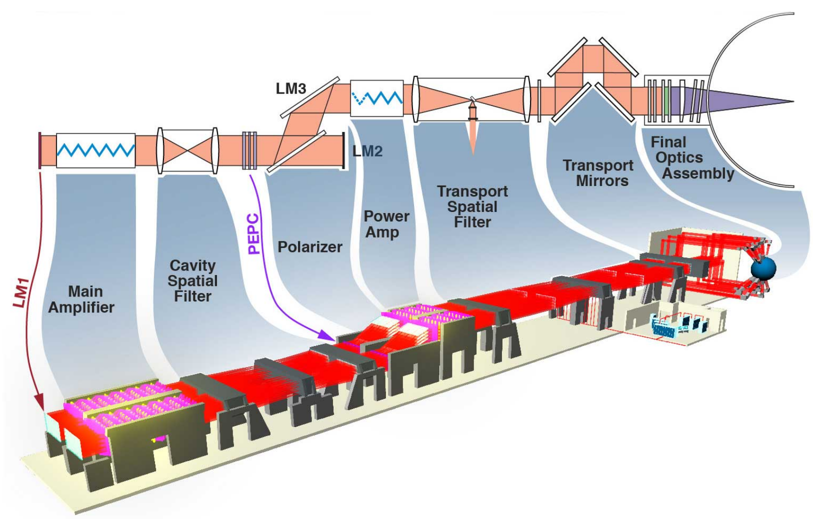

Figure 12: Laser amplification process (Laboratory, 2022)

4.3 Energy harnessing

The energy from ICF reactors is harnessed in a similar way to tokamaks and MCF reactors, through the use of a blanket that surrounds the fusion. The blanket generally contains water that when heated, can run turbines connected to generators, generating usable electrical energy. The fusion reaction takes place within an enclosure known as the target chamber which converts the kinetic energy of the neutrons into thermal energy that can be transferred into water to run steam turbines to generate electricity.

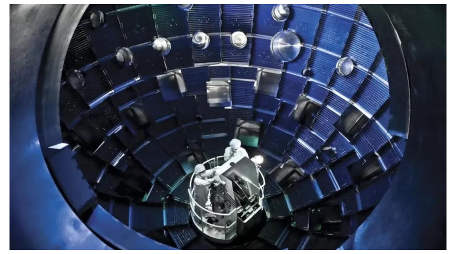

Figure 13: Target chamber (Taylor, 2014)

4.4 Advantages of inertial confinement fusion

A main advantage of ICF reactors is their high energy density. ICF achieves fusion by rapidly compressing a small pellet of fusion fuel, such as a mixture of deuterium and tritium which can achieve incredibly high energy output from a minuscule amount of fuel. The efficiency of energy production in ICF, theoretically, could surpass that of MCF, where the plasma must be maintained at fusion conditions continuously over long periods, requiring substantial energy inputs for magnetic field generation and plasma heating.

Additionally, ICF reactors are safer than MCF reactors due to the fact that ICF systems are run in short pulses which means a lower chance of a runaway reaction or unstable plasma that can cause damage in MCF reactors. The long run times of MCF reactors can lead to the possibility of plasma instabilities that can cause damage to the reactor.

ICF reactors are more scalable and versatile as compared to MCF reactors. ICF reactors have more potential to be designed for different power outputs, accommodating a range of energy needs from small, local power plants to large, grid-scale energy production centers. Due to the pulsed nature of ICF, ICF reactors could allow for modular energy production strategies, adapting to demand fluctuations more dynamically than MCF reactors, which require continuous operation to maintain plasma conditions.

4.5 Disadvantages of inertial confinement fusion

A large disadvantage to ICF reactors is their difficulty in achieving net energy gain, where the amount of energy produced by the fusion reaction exceeds the amount of energy put into the system to initiate and sustain the reaction. ICF suffers from many inefficiencies in its different systems, primarily during compression, heating, and energy capture. The laser amplification process that is used in NIF's ICF reactor has efficiencies of 1 to 1.5% and steam-driven turbine systems are around 35% efficient, meaning fusion gains would have to be on the order of 125-fold just to energetically break even.

Similar to ITER's tokamak reactor, NIF's ICF uses deuterium and tritium as the fusion reactants. However, as was previously stated, tritium is a rare element on Earth with 7.3kgs in total reserve, meaning using tritium as a fuel would be unsustainable. ITER's tokamak works around this by containing a lithium breeding layer within the vessel wall to produce more tritium. However, NIF's ICF reactor doesn't have this, and would be difficult to incorporate a lithium breeding reaction into ICF systems.

ICF reactors work using fusion pulses, where each pulse uses up the fuel in the pellet. Once the fuel has undergone fusion, the pellet needs to be replaced so that the reactor can run again. This means that continual energy production isn't possible with ICF reactors unless large energy storage banks such as a capacitor array are used. Time needs to be spent changing the fuel pellets in between reactions which limits the amount of possible reactions in a given time.

ICF reactions work in pulses, meaning that continual energy production is not possible. This means that some sort of system such as large capacitor banks need to be used to deliver continual energy to a power grid or device. Furthermore, this can mean that energy is lost in between pulses such as reheating materials or cooling down different materials could lead to wasted energy.

5 Magneto-inertial fusion

Magneto-inertial fusion (MIF) is another option for fusion on Earth. However, MIF is a much less developed technology, with the only main contributor being Helion, a private American company. MIF uses a combination of both magnetic and inertial confinement fusion. MIF involves using magnets to create two highly compressed rings of plasma, and then accelerate the two rings towards each other while increasing temperature and pressure, resulting in fusion. (Helion, 2024)

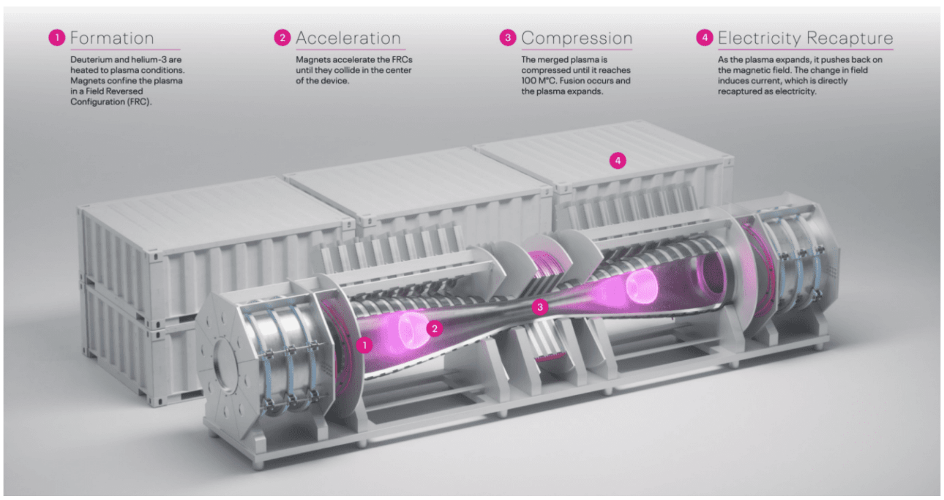

Figure 14: Magneto-inertial fusion system overview (Helion, 2024)

Helion's most advanced reactor, Trenta, uses aneutronic fusion, meaning instead of harnessing the energy through a neutron, the energy is carried via a proton. (Helion, 2024) Aneutronic fusion can contribute to the overall efficiency and allow for the efficient transfer of thermal energy. Helion's fusion reactor uses, unlike ITER's tritium and deuterium, helium-3 and deuterium, creating helium-4 and a hydrogen atom. Aneutronic fusion allows for higher efficiency due to the fact that it can eliminate the need for an intermediary form of energy, which, in ITER's case, are the concrete walls and the cooling water. Aneutronic fusion allows for a direct conversion of the kinetic energy of charged particles into electrical energy through the use of a strong magnetic field that the charged particles push against.

Trenta uses 2 mirror rings of plasma on either end of the reactor, then fires them at each other by sequentially activating magnetic coils to squeeze and compress the rings of plasma towards each other. They collide at the center, traveling at 300km/s, using their kinetic energy to overcome the electrostatic repulsion between ions, fusing them and making new nuclei in the process. (Engineering, 2022)

Trenta starts by heating the gas to approximately 1,000,000°C, to tear the electrons away from the nucleus, forming a charged plasma. This plasma then forms a closed field-reversed configuration, where magnetic fields confine the plasma without a central penetration, having the form of a self-stable torus, similar to a smoke ring. This is done by pulsing the magnetic coils to reverse the magnetic fields, trapping the magnetic energy in a closed field. The plasma then gets accelerated towards the center through a process known as peristaltic acceleration, where the magnetic coils are sequenced to squeeze the plasma forward, accelerating it out of the plasma formation section into the higher field compression section. (Helion, 2024)

Figure 15: Helion's MIF reactor (Wang, 2023)

As the plasma gets accelerated towards the center, it gets compressed, and through adiabatic compression, it increases in pressure and temperature. As the plasma enters the main compression section, it is in the order of 10,000,000°C, traveling at over 300km/s. The plasma will then meet an identical ring that was made symmetrically on the other side, colliding in the center. They both stagnate and stop in the center as their kinetic energy is converted into thermal energy. At this point, the plasma should now be in the order of 10-20,000,000°C, sitting in the center, ready for fusion. The magnetic field is then rapidly increased, compressing the plasma further, bringing the plasma to over 100,000,000°C. At this point, the fusion reactions start to occur, fusing the deuterium and helium-3 to create helium-4 and hydrogen, applying pressure back on the magnetic fields.

5.1 Fuel

Unlike ITER, Helion is choosing to use deuterium and helium-3 as its reactants as opposed to ITER's deuterium-tritium mixture due to the rarity of tritium. There is an estimated 20kg of it in global reserves and a single commercial-scale tokamak is expected to use around 300g of tritium each day, giving an estimated 2 months of operation with the world's entire current supply.

Despite the problems with tritium, it has a 50 times greater reactivity at 300,000,000°C with deuterium than deuterium has with helium-3, meaning it would be able to produce, on average, 50 times more energy than deuterium-helium-3 reactions. At lower temperatures, such as those that are used in Trenta and ITER, helium-3 and deuterium reactions are 1000 times less reactive than deuterium-tritium reactions at 100,000,000°C. (ITER, 2024a) (Engineering, 2022)

Also, the reaction with deuterium and helium-3 can, half the time, cause the deuterium to react with itself, which half of the time, will release a neutron, meaning for every 4 deuterium and helium-3 reactions, a radioactive neutron will be produced. This is further emphasized at temperatures around 100,000,000°C where the deuterium-deuterium reactivity is 7 times higher than that of helium-3-deuterium, meaning a lot of radioactive neutrons will be produced when trying to create energy.

5.2 Fusion containment

Similar to magnetic confinement fusion, magneto-inertial fusion uses magnets to confine the fusion and keep it away from the walls. The magnets are used both for accelerating the plasma rings towards each other and also for containing the plasma away from the walls of the reactor. Trenta uses a field-reversed configuration to prevent plasma energy losses and to contain the plasma. This shapes the plasma into a stable, torus shape.

The reaction with deuterium and helium-3 will, a quarter of the time, produce a radioactive neutron. Neutrons are estimated to be 10 times more deadly than a similar gamma ray, and unlike gamma rays, the neutrons will make surrounding objects radioactive even after the machine is switched off. To stop such neutrons, you need at least 1 meter of dense material surrounding your fusion reaction to contain the neutron, which Helion does not yet have. This means the current versions of magneto-inertial are unable to perfectly contain the plasma and its by-products. (Helion, 2024)

5.3 Energy harnessing

Unlike tokamak systems which harness the energy of fusion by converting the neutron's kinetic energy to thermal energy in water to produce steam, Helion uses the change in magnetic fields to generate electricity. Avoiding the intermediary steps involving steam and spinning turbines should make Helion's fusion energy theoretically more efficient. Each fusion reaction between deuterium and helium-3 makes 18.3 MeV as opposed to deuterium and tritium's 17.6 MeV, and on a mass basis, this is 4 times more energy than a uranium-235 fission reaction.

5.4 Advantages of magneto-inertial fusion

Magneto-inertial fusion reactors can be smaller and more portable than larger MCF or ICF approaches. MIF technologies are also more versatile and scalable compared to more traditional fusion methods. This flexibility could make MIF suitable for a variety of applications, ranging from small-scale research experiments to large-scale power generation facilities. This could have special use cases such as being a backup power source for different systems and electrical grids. Smaller systems can be beneficial in many situations compared to larger, and more complicated systems

Furthermore, MIF aims to require less energy to achieve confinement compared to traditional ICF or MCF approaches. The magnetic fields help to confine the plasma, reducing the rate of energy loss and potentially leading to a more favorable energy output-to-input ratio. The combination of magnetic fields and inertial compression in MIF can help reduce the plasma instabilities that are common in both MCF and ICF systems. Magnetic fields can help to stabilize the plasma during compression, potentially leading to more uniform and controlled fusion conditions.

Also, by combining aspects of MCF and ICF, MIF can potentially simplify some of the engineering challenges associated with achieving fusion. For example, magnetic fields can reduce the physical stress on the containment vessel by providing a form of non-contact support to the plasma.

Additionally, Helion's Trenta makes use of direct conversion of fusion energy into electricity, bypassing the inefficiencies associated with traditional thermal conversion processes. This could lead to more efficient power generation systems.

5.5 Disadvantages of magneto-inertial fusion

MIF is a less developed technology compared to MCF or ICF which have had substantial amounts of funding from different institutions and governments. This puts MIF at a disadvantage as more research and development needs to be done on the technology, meaning more funding will be needed for an operational MIF device. Competing for funding against more developed technologies like MCF and ICF will be difficult for MIF.

To quickly compress and accelerate the plasma together to achieve fusion requires a large amount of energy delivered quickly. To supply this power, dedicated capacitor banks are needed to quickly power the magnetic coils because pulling that kind of energy from the grid would be impossible. Having large capacitor banks adds complexity and costs to the fusion device.

The use of aneutronic fusion in Helion's Trenta is impacted by a phenomenon known as bremsstrahlung, in which electromagnetic radiation is produced by the deceleration of a charged particle when deflected by other charged particles, meaning a lot of the energy contained by the fusion in the reactor gets dissipated as electromagnetic radiation and is lost. (Engineering, 2022)

6 Factors that impact the development and commercialization of fusion energy

6.1 Economic factors

The cost of research and development of nuclear energy is one that many governments will need to consider when moving to nuclear power. The ITER project had an initial project budget of €6 billion. However, the total price of construction and operations is projected to be from €18 to €22 billion, with other estimates placing the total cost between $45 billion and $65 billion. Since 1950, the U.S. government has put federal money into fusion research and today invests approximately $700 million per year into research and development. (Cho, 2021)

Historical US Funding on Fusion Energy (Margraf, 2021)

Year	Enacted Budget (Million USD)	ITER Funding (Million USD)	CPI Inflator	Inflation-Adjusted Enacted Budget (Million USD)	Inflation-Adjusted ITER Funding (Million USD)
2000	250.0	-	172.0	376.3	-
2001	255.0	-	176.9	373.3	-
2002	248.5	-	179.8	358.0	-
2003	240.7	-	184.1	338.6	-
2004	255.9	3.2	189.0	350.7	4.3
2005	266.9	5.5	195.2	354.1	7.2
2006	280.7	15.9	201.5	360.7	20.4
2007	311.7	42.0	207.4	389.2	52.4
2008	294.9	26.1	215.4	354.6	31.3
2009	394.5	124.0	214.5	476.3	149.7
2010	417.7	135.0	217.8	496.7	160.5
2011	367.3	80.0	224.3	422.5	92.4
2012	393.0	105.0	228.1	446.1	119.2
2013	377.8	124.0	231.5	422.5	138.7
2014	504.7	199.5	233.4	560.0	221.4
2015	467.5	150.0	235.0	515.1	165.3
2016	438.0	115.0	240.0	472.7	124.1
2017	380.0	50.0	245.0	401.7	52.9
2018	532.1	122.0	249.7	552.0	126.6
2019	564.0	132.0	255.4	571.9	133.8
2020	671.0	242.0	259.0	671.0	242.0
2021	425.2	107.0	-	425.2	107.0

6.2 Societal factors

Many nations, such as South Korea and Japan, have been planning to phase out nuclear power for many years after accidents like the Fukushima disaster in 2011. Many nations are worried about the problems that nuclear energy could bring. However, many of these nations are also realizing that to become truly carbon neutral, nuclear power must be incorporated into their energy supply. Examples of such cases include South Korea and Japan, which are moving back to nuclear power to try and become carbon neutral as soon as possible.

Due to past problems with nuclear power, it has caused skepticism from the general public. The stigmatizing effect of depleted uranium from nuclear fission has negatively impacted the public's attitude toward nuclear power in general, including nuclear fusion. This has caused many to believe that nuclear power is unsafe and shouldn't be used at all. Disasters such as Chernobyl and Fukushima have caused the general public to relate such disasters with nuclear energy instead of just nuclear fission, causing them to believe that such disasters could be caused by nuclear fusion. However, nuclear power will most likely be essential if mankind wants to move away from fossil fuels and carbon-based energies. Public opinion can affect and impact the investments in nuclear fusion research and development, as well as affect the regulatory environment, which in turn can impact the cost of nuclear power. As society develops and becomes more advanced, energy will be an ever-growing necessity, requiring more massive plants and innovative new technologies to keep up with demand. (Waltar & P, 2018) (Public, 2024) (Jones, Yardley, & Medley, 2019)

Most people who understood fusion would agree that if all the facts surrounding nuclear technology were fairly and accurately reported, the media could be one of the most powerful forces in promoting the development of nuclear power. However, fair and accurate reporting does not always mean success for a media enterprise that relies on advertising for its livelihood. Faced with the intense pressures of staying in business in a free market atmosphere, the media are fundamentally in the entertainment business, leaving the media a difficult tool to use. If media companies were to accurately report on nuclear fusion, it would be possible to change the public's opinion on nuclear energy, representing it as a viable solution to fossil fuels and carbon-based energies.

6.3 Advantages of fusion

Nuclear fusion is often considered the holy grail of energy production due to it having the potential to provide an almost unlimited source of energy while also being sustainable. It uses the fundamental forces of our universe to generate usable power for our society. Many naturally occurring objects such as stars or solar systems rely on nuclear fusion to exist. It allows for long-term, sustainable, economical, and safe energy that can be harnessed and used. Fuel is inexpensive and abundant in nature, while the amount of long-lasting radioactive waste and greenhouse gases produced is minimal. Additionally, nuclear fusion is a highly efficient and effective source of energy.

6.4 Disadvantages of fusion

Despite its advantages, there are still many challenges fusion still faces. The requirements for fusion to occur is a large technological challenge we must face to create self-sustaining fusion. The high temperatures and large gravitational pull of stars create ideal conditions for fusion, however, on Earth, these conditions are very difficult to mimic and create. Additionally, even though nuclear fusion produces much less radioactive waste than fission, this radioactive waste still needs proper disposal and must be taken care of. Finally, fusion is still underdeveloped, needs additional research and development. To get practical net energy, a lot of testing will still need to be done to make fusion worth developing.

7 Current state of fusion energy

Fusion energy is still highly experimental and will take time to become a commercial source of energy. Many more millions of dollars and many more years will need to be spent on nuclear fusion power for it to be used commercially. It is not yet a viable source of energy for the general public but significant progress has been made in the field in recent years. Many projects are aiming to make fusion commercially available but many technological challenges must still be overcome for them to succeed.

8 Implications of moving to nuclear power

The transition to nuclear fusion will allow for near-unlimited energy, able to reverse the effects of fossil fuels on the environment and allow energy to be safe and secure. However, it will take many years to develop and will cost billions of dollars to be able to test and research fusion. Moving to fusion would allow for a clean and sustainable source of energy, and we won't have to consider the harmful impacts of energy produced by fossil fuels on human health and the environment. Additionally, fusion energy would provide better energy security, reducing our reliance on finite resources, and would mitigate geopolitical conflict over oil, gas, and other fossil fuels. It would also increase economic opportunities, allowing for more energy to be used in industries such as manufacturing or engineering.

However, there are also many cost and deployment challenges that fusion faces. The construction and operation of nuclear power plants would require new technologies and large investments by companies and governments. This would require lots of funding and societal acceptance for the required focus and funding that governments and companies will need to develop fusion technologies. The development of fusion will cause lots of money and energy to be spent on developing the required technologies.

9 Conclusion

Nuclear fusion presents a captivating alternative to the reliance on fossil fuels, offering a beacon of hope for a sustainable and carbon-neutral future. However, fusion still remains in the experimental phase, with significant advancements needed to ensure its safety and scalability for widespread commercial adoption. Through the use of fusion, we could address and potentially reverse many of the environmental crises that currently afflict our society. This technology promises not only to alleviate the pressures of climate change but to catalyze a transformation towards a more sustainable and resilient global ecosystem.

Nuclear fusion, by its very nature, offers a virtually limitless, clean energy source, producing minimal to no greenhouse gas emissions. Its implementation could drastically reduce our dependence on fossil fuels, which are the primary contributors to carbon dioxide emissions and global warming. As a result, fusion energy could play a pivotal role in slowing, halting, or even reversing the adverse effects of climate change, such as extreme weather conditions, rising sea levels, and the loss of biodiversity.

Whether the power plants maintaining the fusion use magnetic confinement, inertial confinement, or laser confinement, the positives of using fusion significantly outweigh the negatives, being a sustainable and near-limitless source of energy. Magnetic confinement allows for better scalability, being better able to power electrical grids for longer periods of time, while both inertial confinement and laser inertial confinement could be made smaller and work well as smaller, modular power sources.

The adoption of nuclear fusion would create a new era of environmental health. Air and water pollution, caused by the extraction and burning of fossil fuels, would significantly decrease. Furthermore, the shift to nuclear fusion could stimulate global economic growth in a sustainable manner. It could allow for advancements in technology and infrastructure, creating jobs and promoting economic activities that align with environmental conservation and sustainability goals.

Ultimately, nuclear fusion energy offers a beacon of hope for not only mitigating the impacts of fossil fuels on our planet but for paving the way towards a future where humanity coexists with the natural world. It will allow for opportunities we didn't have before, not having to compromise our environment for technological and societal advancement.

10 Future of fusion

The future of fusion holds many possibilities and is still unknown. Fusion power could be the holy grail of energy, being sustainable and carbon neutral, as well as being highly scalable, and capable of powering nations and planets. In 20-30 years, fusion energy will most likely be adopted by many governments to power their nations. Fusion energy still needs developing but soon, fusion energy could be possible and would only need commercializing to become a worldwide technology.

References

Bahmani, J. (2024, Jan). Heating effect of t3he fusion plasma by injecting beam of deuteron. *Indian Journal of Physics/Indian journal of physics/Indian Journal of Physics and Proceedings of the Indian Association for the Cultivation of Science*, *98*(6), 2197–2204. Retrieved from https://link.springer.com/article/10.1007/s12648-023-02981-9 doi: https://doi.org/10.1007/s12648-023-02981-9

Birtannica. (2024). Retrieved from https://www.britannica.com/science/Coulomb-barrier

Cartlidge, E. (2022, Dec). *National ignition facility demonstrates net fusion energy gain in world first – physics world.* Retrieved from https://physicsworld.com/a/national-ignition-facility-demonstrates-net-fusion-energy-gain-in-world-first/

Cho, A. (2021). Retrieved from https://www.science.org/content/article/cost-skyrockets-united-states-share-iter-fusion-project

Clifford, C. (2022, Sep). *Feds commit 50 million to for-profit nuclear fusion companies, chasing the "holy grail" of clean energy.* CNBC. Retrieved from https://www.cnbc.com/2022/09/26/feds-commit-50-million-to-for-profit-nuclear-fusion-companies.html

EESI. (2023). *Fossil fuels — eesi.* Retrieved from https://www.eesi.org/topics/fossil-fuels/description

Engineering, R. (2022, Dec). *A new way to achieve nuclear fusion: Helion.* Retrieved from https://www.youtube.com/watch?v=_bDXXWQxK38

Helion. (2024, Mar). Retrieved from https://www.helionenergy.com/

Hyperphysics. (2024). Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/coubar.html

IAEA. (2021, Jun). Retrieved from https://www.iaea.org/bulletin/magnetic-fusion-confinement-with-tokamaks-and-stellarators

ITER. (2024a). Retrieved from https://www.iter.org/

ITER. (2024b). Retrieved from https://www.iter.org/mach

Jones, C. R., Yardley, S., & Medley, S. (2019). *The social acceptance of fusion: Critically examining public perceptions of uranium-based fuel storage for nuclear fusion in europe* (Tech. Rep.). UK.

Kiger, P. J., & Freudenrich, C. C. (2021, Jan). *How nuclear fusion reactors work.* HowStuffWorks. Retrieved from https://science.howstuffworks.com/fusion-reactor3.htm

Labman. (2024). Retrieved from http://labman.phys.utk.edu/phys222core/modules/m12/nuclear_energy.html

Laboratory, L. L. N. (2022). Retrieved from https://lasers.llnl.gov/about/how-nif-works

Lind, J. (2022, Dec). *Recent advances in indirect drive icf target physics.* Retrieved from https://fire.pppl.gov/iaea04_lindl.pdf

Margraf, R. (2021). *A brief history of u.s. funding of fusion energy* (Tech. Rep.). California US.

Public, A. (2024). *Assessing public attitudes to nuclear fusion energy – analysis - iea.* Retrieved from https://www.iea.org/articles/assessing-public-attitudes-to-nuclear-fusion-energy

Shutterstock. (2024). Retrieved from https://www.shutterstock.com/image-vector/nuclear-fusion-energy-diagram-reaction-models-1501925243

Taylor, A. (2014, Jan). The Atlantic. Retrieved from https://www.theatlantic.com/photo/2014/01/the-national-ignition-facility/100659/

TWI. (2024). Retrieved from https://www.twi-global.com/technical-knowledge/faqs/what-is-a-tokamak

Waldrop, M. M. (2024, Jan). *Can the dream of fusion power be realized?* canarymedia. Retrieved from https://www.canarymedia.com/articles/nuclear/can-the-dream-of-fusion-power-be-realized

Waltar, A., & P, U. (2018). *Social-political factors influencing the expansion of nuclear power* (Tech. Rep.). Texas US.

Wang, B. (2023, Feb). *Helion energy developing two new fusion reactor prototypes — nextbigfuture.com.* Retrieved from https://www.nextbigfuture.com/2023/02/helion-energy-developing-two-new-fusion-reactor-prototypes.html

Wikipedia. (2024, Apr). *Nuclear fusion.* Wikimedia Foundation. Retrieved from https://en.wikipedia.org/wiki/Nuclear_fusion