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Narrative Review Article

Nuclear Fusion as a Future Energy Source: Safety, Challenges, and Prospects

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ABSTRACT

Nuclear fusion is a clean energy source which could help replace fossil fuels to minimize the harmful global impact of climate change. A number of organizations globally have built nuclear fusion reactors, but none of them are currently commercially viable. This review assesses nuclear fusion as a potential energy source for the future, identifying key risks, advantages, and next steps. Hazards identified include explosions, plasma instabilities, and magnetic discharge. Although these risks exist, the likelihood for these accidents to occur was found to be minimal and appropriate safety measures are available. Key challenges that emerged are limited fuel supply and high cost. The primary advantage of nuclear fusion as an energy source is its efficiency (one gram of fuel can produce as much energy as ten tons of coal). A review of historical progress, vital success metrics, and projected future development of nuclear fusion indicates that nuclear fusion could be ready for commercial application as early as 2050. Future research should focus on achieving ignition and self-sustaining plasma to reach commercial viability.

Keywords: Nuclear fusion; clean energy development; tokamak reactor; plasma confinement; tritium supply; ITER; energy policy

INTRODUCTION

The world's climate has changed drastically in the last six decades, greatly affecting agriculture and ecology and increasing both the frequency and magnitude of natural disasters (1). In OECD countries, which include the most developed economies such as the US and the UK, fossil fuels provide 80% of all energy produced (2). Unfortunately, these energy sources also produce carbon dioxide, which is a major driver of global warming and climate change (2). Solar, wind, and other renewable energy alternatives all have drawbacks due to their high cost and resource demand, with the initial cost noted as being particularly high for solar energy and hydropower (3). Some renewable sources, like wind and solar, rely on the weather, which is inconsistent, while others may affect migratory birds or marine wildlife (3, 4). Nuclear fusion is a promising energy source for the future because it avoids the pitfalls of other renewables while sharing the benefits of zero carbon emissions. However, there are several limitations that must be taken into consideration when considering nuclear fusion as a primary energy source.

Nuclear fusion occurs when two atomic nuclei fuse together to form a singular nucleus, producing an amount of energy which is several million times greater than that generated by fossil fuels (5). Isotopes are atoms of the same element that have different numbers of neutrons. In nuclear fusion, two isotopes of hydrogen: tritium and deuterium fuse together to form a helium ion and a free neutron (6). The mass of the resulting helium nucleus is less than the combined mass of the two original hydrogen

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nuclei, and the lost mass is transformed into an immense amount of energy. This is in accordance with Einstein's mass-energy equivalence equation (7). Nuclear fusion reactors function by heating up hydrogen until it reaches the temperature necessary for fusion, and then capturing and converting the energy from the reaction to produce electricity (5).

Z-pinch is an early nuclear fusion method developed by the U.S. and the U.K. in the 1940s (8). Inertial confinement fusion uses energy, often in the form of heat, to compress the plasma in order to cause fusion and release energy (9). Z-pinch is both an inertial and magnetic confinement system which uses Lorentz force for compression. Magnetic confinement uses magnetic fields to alter the direction and confine the electrons of the plasma, creating a virtual cathode which acts as a barrier (10). The addition of a high temperature creates massive amounts of pressure (11). Another prevalent nuclear fusion reactor type is the tokamak, a donut shaped magnetic confinement device designed to heat hydrogen plasma with the goal of achieving controlled nuclear fusion. The tokamak was originally developed by what was then the USSR in 1958 (12).

Recent research on nuclear fusion is primarily focused on how superconductivity can be used in magnetic confinement devices such as tokamaks (13). Since their invention, many notable tokamaks have since been created around the world, including the JET (Joint European Torus) in the UK which was operated from 1983 to 2023 (14). The JET Deuterium-Tritium (D-T) experiments demonstrate reduced energy losses with benefits for future tokamak reactors (15).

Research on various designs of nuclear fusion reactors such as stellarators, lasers, and tokamaks is ongoing (16). A number of other organizations globally have built nuclear fusion reactors, including Princeton Stellarators and Helion Energy in the United States, Renaissance Fusion in France, and UK Atomic Energy Authority (UKAEA) in the United Kingdom (17). The ITER (International Thermonuclear Experimental Reactor) was built in France in 2013 and is currently beginning a new phase of experimentation (18).

High-Temperature Superconducting (HTS) Magnets are an important part of tokamaks that will help create more compact reactors at a lower price. Commonwealth Fusion Systems (CFS) and MIT are leading the research for HTS technology (19). Efforts in Inertial Confinement Fusion (ICF) research have also been made recently to advance laser-plasma interaction science, diode-pumped laser systems, and repetition rate (20). In addition to lasers and tokamaks, another fusion technique under consideration is Field-Reversed Configuration (FRC), which prioritizes size reduction and low neutron production (21). Notable projects using FRC include the Princeton Field-Reversed Configuration (21) and Helion Energy (22). Magnetized Target Fusion is another fusion technique merging magnetic and inertial concepts, with key companies including General Fusion and Zap Energy (23).

In addition to studies that focus on technical innovation for nuclear fusion, further research is necessary to improve its economic viability. Financial analysis involving cost modeling is incredibly important to ensure that fusion is cost effective and to avoid driving up prices (24). Tritium, one of the components of fusion fuel, is scarce, and the facilities responsible for producing tritium do not produce enough to sustain commercial nuclear fusion power plants (25). Canadian Nuclear Laboratories (CNL) and UKAEA are supporting tritium research in order to keep up with tritium demand for commercial reactors. One method under consideration is lithium breeder blanket technology, which interacts with neutrons to breed tritium fuel (26).

Commercial nuclear fusion that can produce more energy than it requires to run both safely and at a relatively low cost has not yet been achieved and further advancements are needed to make this vision a reality. This review provides an assessment of the feasibility of nuclear fusion as a potential energy source for the future. Safety, challenges, advantages, and other factors are discussed and a timeline of the development of the technology is presented.

CHALLENGES AND ADVANTAGES TO IMPLEMENTATION

A major challenge for the widespread implementation of nuclear fusion is the limited supply of tritium (one of the hydrogen isotopes responsible for nuclear fusion). Tritium is generated in Canada Deuterium Uranium (CANDU) reactors within Tritium Removal Facilities (TRF), which only produces around 130 g of tritium per year (25). As of 2023, tritium inventory is limited to just two CANDU TRFs, one in Canada, and another in South Korea. Full-scale reactors such as CFETR and DEMO require multiple kilograms of tritium each to have an effective startup (26). In other assessments, the annual tritium consumption of a fusion power plant operating at 1GW fusion power was calculated to be ~55.6 kg per full power year (FPY) or ~152 g per full power day (FPD) (34). Given this need, the lack of tritium presents a major challenge to the advancement of nuclear fusion technology.

In addition to the challenge of tritium availability, another important hurdle for the implementation of nuclear fusion is cost. Building a nuclear fusion power plant could cost several billion dollars (24). Therefore, it is important for the efficiency of the power plants to increase in order to make their development more cost effective. For example, size, a significant factor that drives up the cost of a power plant, can be optimized by carefully designing the inner radius of a spherical tokamak in order to lower the price (24). Competitive fusion after 2040 would require costs around or below ~\$80-100/MWh according to 2020 prices. Modeling of early fusion designs show costs greater than \$150/MWh, therefore competitive fusion will be difficult to attain (35). In addition to affordability, it is necessary to consider proper risk management before nuclear fusion can be successfully implemented.

While nuclear fusion is generally considered to be safe, some accidents may still occur that pose safety hazards (27). Some safety risks include potential explosions, uncontained radioactive waste, loss of control over the plasma, and electromagnetic discharge (28). One factor that minimizes risk is the amount of fuel burned by fusion reactors. Whereas fission reactors (which split uranium or plutonium atoms to release energy) store enough fuel to last several years, fusion reactors only contain enough fuel for a few tens of seconds, making uncontrolled reactions or "meltdowns" essentially impossible (29). Evidence shows that despite the large amounts of fuel required for fusion technology, this low burn fraction means that the maximum amount of energy released in an accident would not compromise the structural integrity of the confinement barriers (28). However, even small risks such as this one must be evaluated.

Plasma instabilities may threaten the stability of the container within the reactor that holds the plasma for fusion. These instabilities are caused by the pressure of the plasma which breaks the magnetic fields that confine it in a phenomenon called tearing instability (30). Typically, at least two confinement systems are required for a fusion reactor in order to provide backup in the event that one fails (27). Magnetic confinement is a leading method for radioactive containment (Figure 1). The energy stored within the strong magnetic fields confining the plasma is quite large, up to 180 GJ in some cases. If the magnet system fails and energy is released into a localized area of the reactor's walls, it can cause the steel to melt and initiate a loss of vacuum accident (28). ITER has planned an accident mitigation system for its magnetic confinement fusion plant, and the system has real-time monitoring and control and stabilization of the plasma. The system uses energy dump resistors which disperses the stored magnetic energy from the confinement system, providing a safe method to manage the energy (31).

While nuclear fusion reactions generate radioactive waste, it is generally considered to be limited. Additionally, the waste generated can be reused once decontaminated, with any remaining waste disposed of in a safe manner (32). A 2017 study by Taylor *et al.* of nuclear fusion power plants such as the ITER facility discovered that the impact on the environment is low, with a limited quantity of long term waste produced, making it unlikely that radioactive waste will accumulate (27).

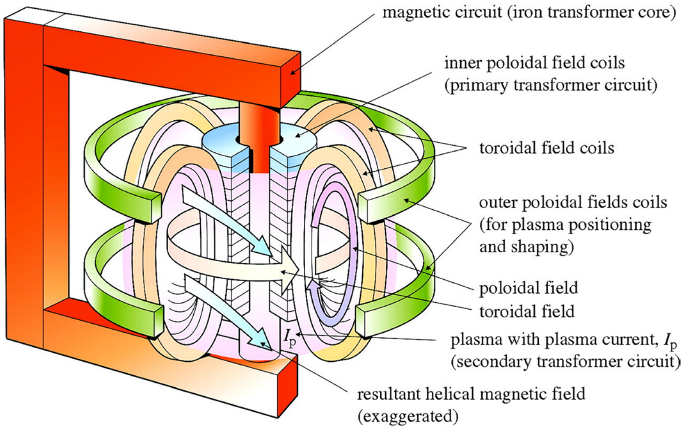

Figure 1. *Magnetic confinement of fusion fuel in a tokamak. The toroidal field coils with the help of a current forms a helical magnetic arrangement which separates the hot plasma from the wall. Source: Smith, Chris Llewellyn and Cowley, Steve. Tokamak schematic Smith.jpg. March 29, 2021* (54)*. CC-BY-3.0. Wikicommons. https://commons.wikimedia.org/wiki/File:Tokamak_schematic_Smith.jpg.*

While plasma instabilities and magnetic discharge may still pose some problems, most other safety issues are controllable. Explosions can occur due to the build up of dust in the reactor, but dust removing mechanisms can be deployed to prevent this (33). Meltdowns, or uncontrolled reactions, are nearly impossible and waste production is generally limited. Energy released in an accident would not compromise the barriers, and can be diverted using energy dump resistors. Given this evidence, nuclear fusion can be considered mostly safe, as long as the few minor risks are addressed.

As for advantages, nuclear fusion conserves more energy than fossil fuels and most renewable energy systems. One gram of deuterium-tritium fuel may be able to produce as much energy as ten tons of coal, without releasing harmful greenhouse gases (36). Nuclear fusion is considered a clean and green energy source, which means it has a low carbon output (37). For example, the UN's Economic Commission for Europe (UNECE) reported in 2022 that nuclear fusion produced CO_2 at the range of 5.1-6.4 g CO2/kWh, the lowest emission rate of all energy sources (16). In the event that fossil fuels such as coal and oil are depleted, nuclear fusion presents an alternative energy source for essential activities (37).

With the constant progression in fusion efficiency, it's quite likely that fusion could become a more effective energy source than other renewables (5). Solar energy is inefficient, converting only a third of the energy received from the sun into a usable form. Additionally, solar panels have a lifespan of 35 years, with efficiency degrading by .5% each year. Wind power efficiency is currently capped at 59.3%, and requires large amounts of open land (38).

THE FUTURE POTENTIAL OF NUCLEAR FUSION

Nuclear fusion's maximum potential can be measured in three main ways: 1) produced electricity share, 2) annual energy cost reduction, and 3) the mitigation of carbon tax. Results from a 2003 study conducted by Tokimatsu *et al*. indicate that nuclear fusion could eventually account for 30% of energy generated globally by 2100, have a global annual cost reduction rate of 1% (or tens of billions of dollars), and a carbon tax mitigation rate of up to 10% (39).

Of the several experimental nuclear fusion facilities that exist, the ITER Tokamak is the most prominent. ITER is designed to generate far more energy than consumed, but many technical challenges still remain (40). ITER is currently planning a new phase of research, the Start of Research Operations (SRO), a 27 month period of significant experimentation with nuclear fusion technology set in 2034 (18).

While the exact timeline for the commercial availability of nuclear fusion isn't known yet, it will likely not occur until the late 2040s or early 2050s. Sadik-Zada *et al*. project that by 2050, fusion may gradually replace fossil fuels as well as renewables if long-term investment is made in the technology (5). In order to reach commercial availability, nuclear fusion reactors must maintain plasma ignition for a prolonged period of time. Ignition happens when the energy that causes the reaction is less than the energy output from the fusion reaction. Ignition has been achieved using inertial confinement fusion, a notable example being the NIF's success on August 8, 2021, generating more than a megajoule of energy (45). The fusion reaction in NIF's ignition only lasted a small fraction of a second (some picoseconds), but commercial nuclear fusion would require ignition for a much longer duration of time, or for it to be done repeatedly (45). In 2024, CEA's WEST Tokamak maintained a plasma for over 22 minutes, which is the current record (46) (Figure 2).

One metric for the commercial viability of nuclear fusion is the "triple product", which incorporates the density of the reactor's plasma, the temperature, and the energy confinement time into a single value (47). The required triple product for self-sustaining plasma (ignition) is 5×10^{21} m-3keVs (10 atm), which has not yet been achieved by tokamak reactors (48). However, the field is experiencing rapid progress. For decades, the highest triple product achieved has tended to double every 1.8 years, as new advancements in fusion technology were made (5). More recently, however, even greater strides have been made. In 2022, US Tokamak Energy's ST40 tokamak achieved a triple product of 6×10^{18} m-3keVs (49) and in 2026, China's HL-3 tokamak produced a triple product of 0.65×10^{20} m-3keVs (50). The progress on the triple product is represented in Figure 3.

The final barrier to commercial availability for nuclear fusion is financial support. While fusion technology is a high risk and high return prospect which provides significant business risks and discourages conventional funding, attitudes have begun to shift. Similar to other high-cost yet potentially transformative scientific endeavors such as space exploration, fusion development has turned to private investors for support. Early stage progress has been made possible by wealthy private investors. Major tech companies are also willing to invest in fusion startups as the risk can be absorbed by their broad investment portfolios (52). Notable private companies investing in nuclear fusion technology include Cenovus Energy, New Enterprise Associates, and Breakthrough Energy Ventures (53).

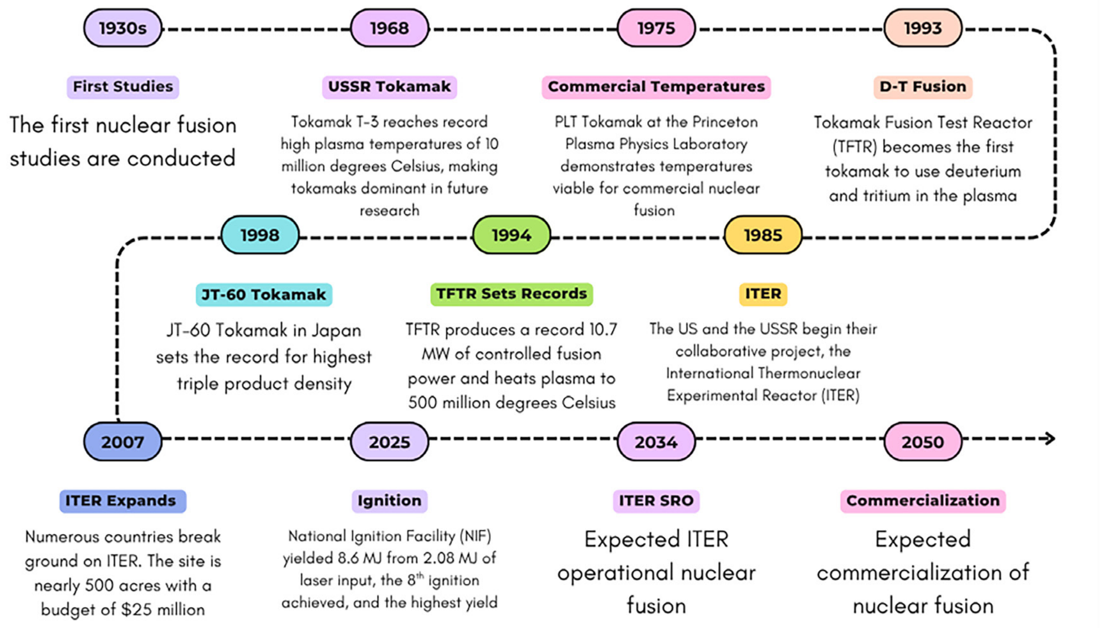

Figure 2. Nuclear Fusion projects timeline. Dates and expected milestones were extracted from a literature search (5, 41, 42, 43, 44).

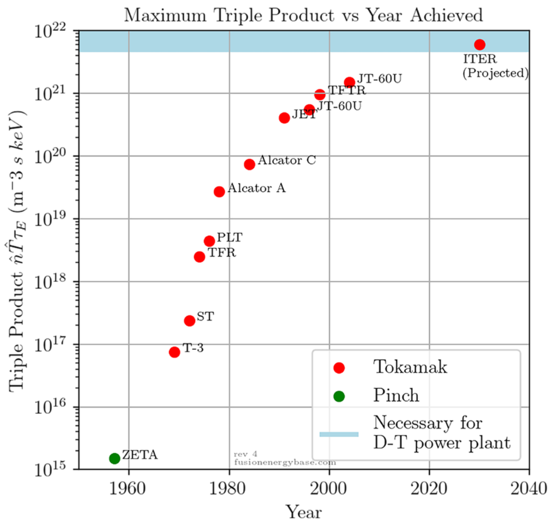

Figure 3. Maximum triple product vs year achieved. Experimental data from Fusion Energy Base. Projected value of ITER from published models (51). CC BY-NC 4.0. The abbreviations correspond to the following reactors: ITER: International Thermonuclear Experimental Reactor, JT-60U: Japan Torus-60 Upgrade, TFTR: Tokamak Fusion Test Reactor (US), JET: Joint European Torus (UK), Alcator C and Alcator A: High-field Toroidal Experiment (Alto Campo Torus), PLT: Princeton Large Torus (US), TFR: Tokamak de Fontenay-aux-Roses (Fr), ST: Symmetric Tokamak (US), T-3: Tokamak-3 (Russia), ZETA: Zero Energy Thermonuclear Assembly (UK), the only non-Tokamak reactor included in the figure.

CONCLUSION

Nuclear fusion is an ideal option for the world's future energy source. It is a clean source of energy, which can replace fossil fuels, and is also much more efficient in terms of fuel to energy output ratio. Nuclear fusion also does not rely on weather patterns, which makes it more reliable than most other clean power sources including wind and solar.

However, in spite of the numerous advances in recent years, nuclear fusion still has many challenges before reaching full commercial viability. Various safety precautions must be taken to avoid problems, most prominently being explosions and instabilities. Nuclear waste also needs to be dealt with, even though the amount produced is limited. Encouragingly, these safety issues are not a large concern as in the event of an accident, even the greatest possible amount of energy released could not destroy the container. Cost poses an additional obstacle, but measures can be taken to increase the efficiency and optimize a reactor. The most important hurdle to viability is the lack of tritium supply.

The broader implications of nuclear fusion should address the limitations listed earlier to attain commercially viable fusion. For example, further research on increasing tritium production would assist in tackling the issue of tritium supply. Advancing reactor technology in order to achieve ignition and exploring expense reduction strategies would address the cost constraint for fusion powered electricity. These advances are necessary in order for nuclear fusion to meet the goal of commercialization by 2050, and generate abundant clean energy.

This review helps the field of energy and nuclear fusion as it provides insight on the major factors related to nuclear fusion's viability as a future energy source and finds that fusion is promising for the world, with the potential to generate electricity using less resources and can help replace fossil fuel usage to slow down global warming.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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