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Nuclear Fusion: The Promise of Endless Energy

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Abstract: This chapter introduces the reader to the fundamentals and reasoning for exploring fusion energy. Fusion, the reaction of two hydrogen atoms colliding, is the process that powers the Sun and stars. Fusion works by turning small amounts of matter into vast amounts of energy. If realized on Earth, nuclear fusion could solve global energy demands for generations to come.

Keywords: fusion, energy, nuclear.

1. Introduction

Energy is essential to everyday life. It is everywhere. It is the basis of life. Energy can be found in many forms such as heat, light, motion, electrical, chemical and gravitational field. Everyday activities revolve around production and use of energy. This includes heating or cooling of buildings, driving or moving merchandise, running machines, communicating, and manufacturing of products. Every economic system of our society from the residential, transportation, commercial to industrial sectors rely on the routine consumption of energy.[1] But what is energy? Energy is the ability of a physical system to do work.

According to the International Energy Agency, currently, the world's energy consumption is around 157 petawatt hours (1.575×10^{17} watt hours). This corresponds to an energy consumption of 5.67×10^{20} J or 13.54 billion tons of oil equivalent.[2,3,4]

Global energy consumption, however, has increased steadily for decades. Yet, even though the global population has tripled in the last 100 years, the energy consumption has increased almost six times (***Figure 1***).[2-Error! Bookmark not defined.] A steady-state population growth coupled with an increased standard of living are attributed to the enormous amounts of energy needed to sustain society's daily activities. Moreover, with the global population projected to grow from 7.7 billion in 2019 to over 9 billion in 2040, energy demands will continue to increase at a very rapid pace. For example, it is expected that, by 2040, the global energy demand and consumption will continue to escalate in the future with projections of 20-30% increase.

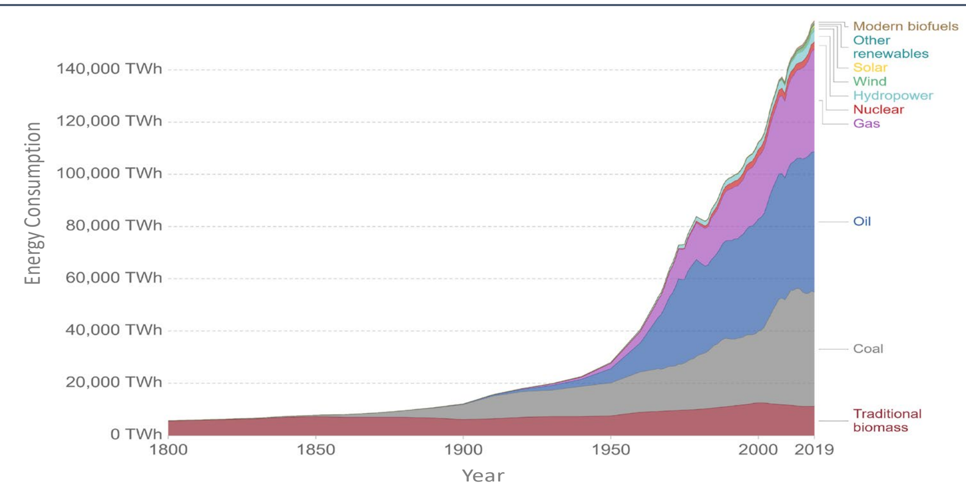


Figure 1. Global direct primary energy consumption from 1800 to 2019 by fuel type.[2,3]

As economic development continues to rise, future energy supplies will be inadequate and potentially depleted. Therefore, energy security is one of the most stringent concerns of our society. For a sustainable and prosperous future, we must ensure continued economic prosperity and population growth. The energy security challenge relies on society's ability to continue to push the boundaries and (a) identify new energy resources, (b) efficiently harness renewable energy resources such as wind, solar, nuclear, biomass and geothermal energy, (c) enhance the efficiency and performance of current energy systems by developing energy efficient vehicles, buildings, etc., and (f) establish appropriate policies and regulations that support and promote a balanced sustainable energy future.

2. Current and Future Energy Resources

Current energy resources fueling our world rely on several primary assets: fossil fuels, nuclear energy, or renewable resources. These major forms of energy have each been discussed through political debate and public policy over the past few centuries since their discovery. Arguments consider the ease of human life, the carbon footprints they leave on the Earth as well as the sustainability of our planet as a whole. Currently, fossil fuels such as oil, natural gas or coal, supply approximatively 80% of the world energy stream (***Figure 2***).

(a) *Coal.* The fuel that launched the industrial revolution, coal, is the most abundant fossil fuel. It is one of the largest sources of electrical generation.**Error! Bookmark not defined.** Major coal reserves are currently found in North America, Europe, and the Asia-Pacific regions, with estimates of one trillion tons of proven coal resources worldwide.[5] With the (usually) inverse relationship of cost/temporary human benefit and positive environmental effect, coal leans most heavily on the side of the former. It is one of the longest and most commonly used forms of energy, but also "*the dirtiest of all fossil fuels*" and a harmful means to fulfilling the same goal. When burned, it adds carbon dioxide and toxic gases, i.e. NOx and sulfur dioxide, to the atmosphere that contribute to climate change and the warming of the Earth. Scientists also consider coal-fired power plants to be "the greatest contributor to mercury pollution" with over 50% of human-caused mercury emissions.[6] Another disadvantage is the process of extraction that can be unsafe, or even deadly, for those lacking the necessary machinery and safety equipment. Its positives are its cheaper cost and abundance that continue its frequent use to this day.[7]

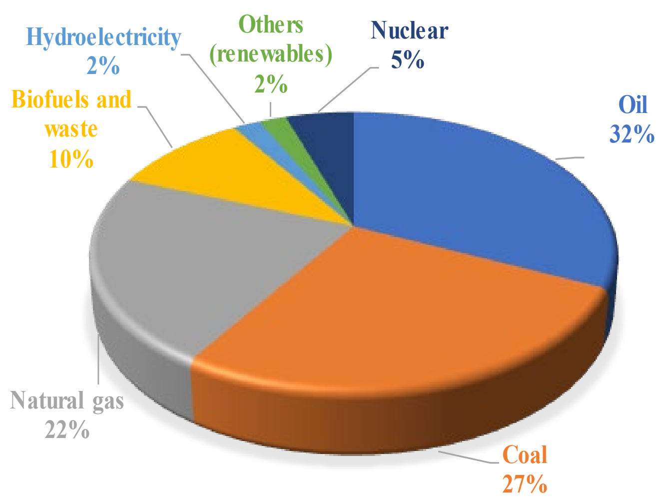


Figure 2. *Total primary energy supply.*[1]

Clean coal technologies that are less polluting have been developed over the years. The most notable clean coal technologies include coal washing, wet scrubbers, ion NOx burners, gasification, CO_2 capture and storage, among others. For example, coal washing relies on a pre-washing step that is achieve before burning. However, many complete and tedious washing steps are needed to remove dangerous minerals before they seep into the air. Other common techniques are using wet scrubbers to limit sulfur dioxide release in the atmosphere, low-NOx burners to limit nitrogen oxides emission, and electrostatic precipitators to limit particulates release. Coal Gasification technology is converting coal to other gases before it is burned.[8] Although these are all beneficial methods to reducing some of the related environmental negatives, harmful pollutants must still be released, despite the enhanced technology that exists. Carbon dioxide and coal's burning by-product gases remain fateful enemies to nature and continue their globe-warming quest with a high carbon footprint. Most notable, however, carbon-based energy assets are limited and cannot provide the energy needed in the future. It is projected that, if the current rate of burning fossil fuel is maintained, fossil fuels will be exhausted in the next several decades.[9]

(b) *Natural gas*. Similar to coal, natural gas may emit carbon dioxide and other greenhouse gases, particularly methane, which makes up its greatest concentration (80-95%). And if you've been watching the news lately, you may have heard of the debate over fracking, the often-harmful process through which oil companies extract shale gas, i.e., natural gas that is found trapped within shale formations, from the Earth. This can be one of the most dangerous and environmentally impacting techniques but employs thousands of laborers each year (1.2 million in the entire industry) and supports the economic success of our country as a whole. We see the same push-and-pull of cost versus the environment, and just as with coal's burning process, fracking is similarly harmful to our world. Aside from this, and from the harmful pollutants released, natural gas is the cleanest form of energy coming from fossil fuels and emits significantly less carbon dioxide than coal and oil.[10] With many countries continuing to use natural gas as their main form of energy, technological improvements have been made to the industry to lesser the negative effects of its extraction. These include dimensional seismic imaging through computational models and CO_2-Sand fracturing that eases the Earth's recovery. Coiled tubing, as well, is a relatively simple improvement that reduces drilling space and therefore leaves a much smaller footprint on the environment. Even more recent innovations include liquefied natural gas and natural gas fuel cells, each which is growing in popularity and improving both the financial and global aspects of generating energy. Liquefied natural gas, however, only makes up "about 1 percent of natural gas used in the United States," so it has a significant way to go in terms of consumption and environmental impact, yet natural gas is still relatively beneficial compared to coal ("Natural Gas and Technology"). Natural gas supplies may only last an estimated 100 to 250 years. The largest oil reserves from Venezuela (20% of global reserves), Saudi Arabia (18% of global reserves), Canada (13% of global reserves), and Iran (9%) could soon be depleted.[11]

As society and the political climate move toward a zero-net carbon economy, adoption of alternative and renewable energy resource is highly encouraged and promoted. A few favorable alternatives on the rise that promise a cleaner and greener future include solar energy, nuclear energy, and energy from wind and biofuels.

(c) *Biofuels.* Biofuels, a mature technology that generates lower carbon emissions than fossil fuels, presently provides around 10% of the total primary energy supplies. However, it is constrained by inadequate land and water available for the crop's stewardship. Further hurdles, such as the increased costs of labor, transportation and storage pose additional barriers toward a profitable worldwide implementation.

(d) *Solar Energy.* In contrast to the aforementioned energy sources, coal, natural gas, and biofuels, solar power is not a fossil fuel; rather, it is clean and renewable, not directly emitting pollutants "into the atmosphere and water supply." It is one of the most environmentally friendly forms of energy, and it has no carbon footprint, meaning it is incredibly beneficial to the Earth. Solar energy is a renewable energy resource. Despite this, consumer drawbacks exist, such as that it is costly to install solar panels and they cannot be easily moved or installed, so some choose not to have them while others' houses are not suitable for their installment. [12] These hindrances significantly limit the role of solar energy in today's world, yet solar technology continues to improve due to the work of scientists and engineers. For example, photovoltaic cells contain internal electrical fields to take in sunlight and concentrating solar-thermal power systems reflect sunlight so it can be converted into heat and stored.[13] Each is a fantastic stride toward sustainability, but solar power has yet to be as widespread - and therefore effective - on a global scale. Solar energy resources rely on the use of solar power and could play a vital role in meeting future energy demands. Nevertheless, solar energy can not be generated throughout the entire day, as it doesn't produce power at night. Large scale implementation requires significant breakthroughs in increasing solar energy conversion's efficiency and storage.

(e) *Wind and tidal*. The wind and tidal supplies are green energy resources that have zero-carbon emissions. While they could provide predictable energy outputs, unfortunately, just as solar energy resources, these are temporary solutions that are hindered by the intermittent availability. The limited land availability, however, obstructs their widespread adoption.

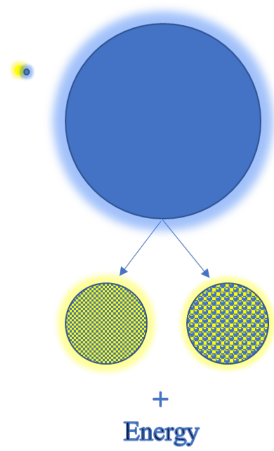
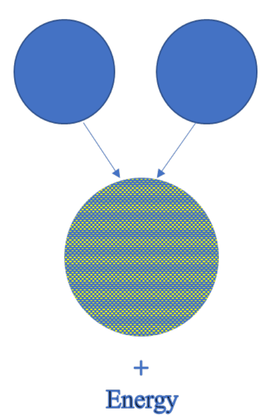
(f) *Nuclear energy.* Nuclear energy promises to unravel society's energy needs dilemma. It is often considered as clean energy and provides a good alternative to the environmental challenges that exist in other energy sources. Whereas others either benefit consumers or the environment, nuclear power benefits both through its lack of emissions, creation of jobs, and ease of use for everyday people. We should mention that because nuclear energy releases zero emissions, both humans and the atmosphere benefit as "acid rain, smog, lung cancer and cardiovascular disease" lessen. It also produces much less waste than most other sources, and takes up only a small amount of land, giving it small land and carbon footprints.

Nuclear *fission* power plants generate energy, in the form of heat and power, by splitting heavy and unstable atoms. Unfortunately, the nuclear fission reactions generate unstable nuclei that are radioactive for millions of years. The chain reactions generated by splitting off heavy nuclei are also often difficult to control and stopped. The process requires the use of highly radioactive materials. It also generates substantial radioactive waste. The radioactive materials pose a risk to the environment and all living organisms for decades.[14] Efficient capture and disposal of the radioactive wastes it is not a trivial task as significant controls must be in place when handling radioactive materials.[14,15,16,17] The long half-life, toxicity, and high energy emitted from radioactive waste makes this a very challenging and complex process.[14-17] The nuclear fission energy is often received with significant public criticism due to numerous safety and proliferation concerns. Even though the fission reactions are the most efficient sources of energy compared to the fossil fuel and/or renewable energy resources, the recent nuclear disasters, such as Chernobyl (1986) and Fukushima (2011), make it difficult for widespread implementation and support from all stakeholders such as public, government, regulators, industry, etc.

Fusion, however, is an environmentally friendly nuclear energy resource, however, that generates 3-4 times more energy than fission. Fusion reaction is the opposite reaction of fission. While both, fusion and fission, are nuclear reactions that generate energy from nuclei, there are however fundamental differences between these two energy generating resources (***Table 1***). For example, in a fusion reaction, atoms fuse together while in a fission reaction, the atoms split into smaller atoms. Fusion reaction byproducts are environmentally safe, while fission reactions generate hazardous radioactive materials. Moreover, fusion reactions can be stopped immediately while the fission chain reactions, once initiated, are more difficult to terminate.

Fusion reactions power the Sun and stars. Through a *nuclear fusion reaction*, every second 600 million tons of hydrogen fuse together in the Sun, generating helium while converting matter into energy.[18] The resulting energy in the form of light and heat makes life possible on Earth. The Sun was born almost 5 billion years ago, nevertheless, it is an endless source of energy each day.

Table 1. *General similarities and differences between fusion and fission reactions.*

Characteristics	**Fission**	**Fusion**
Reaction	Splits a large heavy atom into 2 or more smaller atoms	Fuse 2 or more light atoms into a larger atom
Reaction schematic		
Fuel	Heavy radioactive atoms such as uranium or plutonium	Light atoms such as hydrogen’s isotopes (protium, deuterium and tritium)

Byproducts	Used nuclear fuel and other radioactive atoms	Helium
Uses	Energy	Energy – if realized on Earth
Efficiency	1 million times more energy than any other energy resources, except fusion	3-4 times greater efficiency than fission

For decades the scientific community has focused on exploring ways of replicating and harnessing the energy generated by the Sun on Earth. High temperatures in excess of 100 million degrees must be achieved on Earth for fusion reactions to occur. Unfortunately, no materials on Earth can withstand these extraordinary temperatures. At this high temperature, fuel is turned into plasma. High pressures are also needed to force hydrogen atoms to fuse together. Innovative and clever solutions are needed to meet these challenges to create fusion on Earth. It is believed that fusion energy could embody the quintessential "Holy Grail" paradigm for providing a clean, environmentally friendly and abundant energy resource. If efficiently initiated, harnessed, and sustained, fusion energy could provide us with endless energy for life on Earth.

3. The History of Fusion

Fusion energy could solve global energy demands for millions of years. It has been reported that the amount of energy released in nuclear fusion reactions is 10 million times greater than that of burning fossil fuels.[19] The amount of fuel needed to generate a fusion reaction is significantly smaller compared to any other energy sources, such as fossil fuels, renewable energy, or nuclear fission.[20] This is why a significant smaller amount of fuel is needed to initiate a fusion reaction. Ultimately, the energy produced from nuclear fusion reactions is capable of powering the whole humanity at a relatively low cost.

The concept of fusion was first introduced in the late 1920s (***Figure 3***), by British astrophysicist Arthur Eddington in *Internal Constitution of the Stars*.[21] With a keen interest in trying to understand how energy radiates from stars like the Sun, he suggested that energy from stars is due to the fusion of hydrogen atoms. Eddington presumed that four hydrogen atoms with an atomic mass of 1.00794 amu (atomic mass units) combine in the Sun to create helium with an atomic mass of 4.0026amu. The difference in mass would be converted into energy, according to Einstein's famous relation: $E=mc^2$, where E is energy, m is mass and c is speed of light. This suggests that the fusion reaction from 1 kg of hydrogen would generate $7.5\text{x}10^{14}$ J of energy. This could sustain life on Earth for 10,000 years.

Not long after, Robert d'Escourt Atkinson and Fritz Houtermans provided the first mathematical calculations for the rate of nuclear fusion in stars.[22] In the late 1930s, building on Ernest Rutherford's early nuclear transmutations discoveries, Mark Oliphant (Rutherford's student) experimentally demonstrated a fusion reaction by producing helium-3 and tritium from heavy deuterium nuclei. This was the first time that a fusion reaction was demonstrated experimentally in the lab. Subsequently, Hans Bethe provided calculations showing a star's energy is released through proton-proton reactions. In 1967, Bethe received the Nobel Prize in Physics for extraordinary contributions to the theory of nuclear reactions.[23]

These advances in the foundations of theoretical and experimental concepts inspired scientists and engineers to embark on an ambitious mission to build a fusion device on Earth. Historic advances were made in this field throughout the 1950s-1960s by Soviet scientists Andrei Sakharov and Igor Tamm. They pioneered a unique magnetic confinement configuration in the shape of a hollow donut design that could confine particles at high temperatures. This novel design harnesses the energy of fusion reaction. They coined this toroidal concept - *Tokamak*. Tokamak is an acronym in Russian language for toroidal magnetic confinement. Tokamak design was a monumental achievement that still dominates fusion research efforts today. The first working Tokamak was credited to Natan Yavlinski in 1958. These early successes subsequently launched a series of prolific activities and advancements.

As scientists and engineers embarked on their most enticing journey's yet for creating the endless source of energy for the future, a series of outstanding discoveries were achieved over the next few decades. These include the developments of the (a) Sterallator which is a plasma device that uses intricate external magnets to confine plasma, (b) inertial confinement fusion which attempts to initiate the fusion reaction by heating and compressing a fuel pellet target, (c) z-pinch machines that use electrical currents in plasma to generate magnetic fields that compress it, (d) magnetic mirrors in which electromagnets are used to increase the density of magnetic field lines at the ends of confinement areas, or (e) divertors that remove heat and ash produced in fusion reactions while protecting surrounding vessels from thermal and neutronic loads, and minimizing plasma contamination.

Significant developments were subsequently made by key scientists from the United States, Russia and multiple European countries. In the 1970s, the Joint European Torus (JET) partnership was created in which more than 40 European laboratories started working collaboratively toward achieving fusion energy.

In 1985 at the Geneva Superpower Summit, Soviet Union's leader Mikhail Gorbachev made a historic proposal to then U.S. President Ronald Reagan to create an international collaborative project to develop fusion energy for peaceful purposes. This would be the largest international venture of working toward the developing of fusion energy of its kind. Engagement of the global scientific community would play a pivotal role in this success. A year later an agreement was reached, and the United States, Soviet Union, European Union and Japan embarked on one of the most magnificent and inspiring projects in human history: designing and building the world's largest international mega-fusion facility. It was named the International

Thermonuclear Experimental Reactor (ITER). There are currently 35 countries from around the world working collaboratively to build the first ITER in France.

For fusion process to be considered efficient and self-sustainable the thermal energy output must exceed input energy. The ultimate goal is to achieve fusion energy with a gain factor (Q) of 10. Q of 1 is considered breakeven. For fusion energy to be feasible in terms of input/output energy, Q must be greater than 1. The ITER is projected to produce 500 MW of fusion power, $Q \geq 10$, from 50 MW of heating input power produced from deuterium-tritium plasma. The integration of numerous parts, components and operational technologies needed to operate a fusion power device must be demonstrated before these parameters are met. A tritium breeding module must also be established. By using a 50-50 mix of tritium and deuterium fuel, JET demonstrated a world record of Q = 0.67. A fusion energy output of 16 MW was generated from an input of 24 MW of heating.[24] This success was first demonstrated in 1997. A fusion energy gain factor of Q = 1.25 was demonstrated by Japan's Torus-60 for extrapolated breakeven.[25] The extrapolated breakeven value was obtained from a mixture of protium and deuterium, not tritium. These mixtures are typically more difficult to ignite.

The National Ignition Facility (NIF), the largest laser-based inertial confinement fusion ever built, became operational in 2009. It contains powerful lasers that confine, amplify and focus hundreds of beams into a target fuel (the size of a pencil eraser) in a few billionths of a second. Two million joules of ultraviolet energy and 500 trillion watts of peak power generate high temperature and pressure (180,0000,000 F and 100 atm) needed to fuse hydrogen to release energy in a controlled reaction.[26] In 2018, NIF reported 54 kJ of fusion energy power and a total fusion neutron yield of $1.9*10^{16}$, which double the previous record.[27]

Fusion research is currently at the verge of creating a "burning plasma" in which sufficient heat from a fusion reaction is retained within the plasma and able to sustain the reaction for a long duration.[28] In 2017, the Experimental Advanced Superconducting Tokamak (EAST) reported a record time of 100 second steady state high confinement performance plasma.[29] In 2018 SPARC was formed. It was a collaborative venture between the Massachusetts Institute of Technology and a private fusion company named Commonwealth Fusion Systems. SPARC embarked on a mission to produce 50-100 MW of fusion power to achieve a Q of 2. This is based on a smaller deuterium-tritium burning tokamak device that is compact and uses a stronger superconducting magnet. If successful, SPARC will be the first experimental device to demonstrate a "burning plasma". Completion of ITER is expected to be finalized by 2025 and generate its first plasma. Deuterium and tritium operations are anticipated to start in 2035.

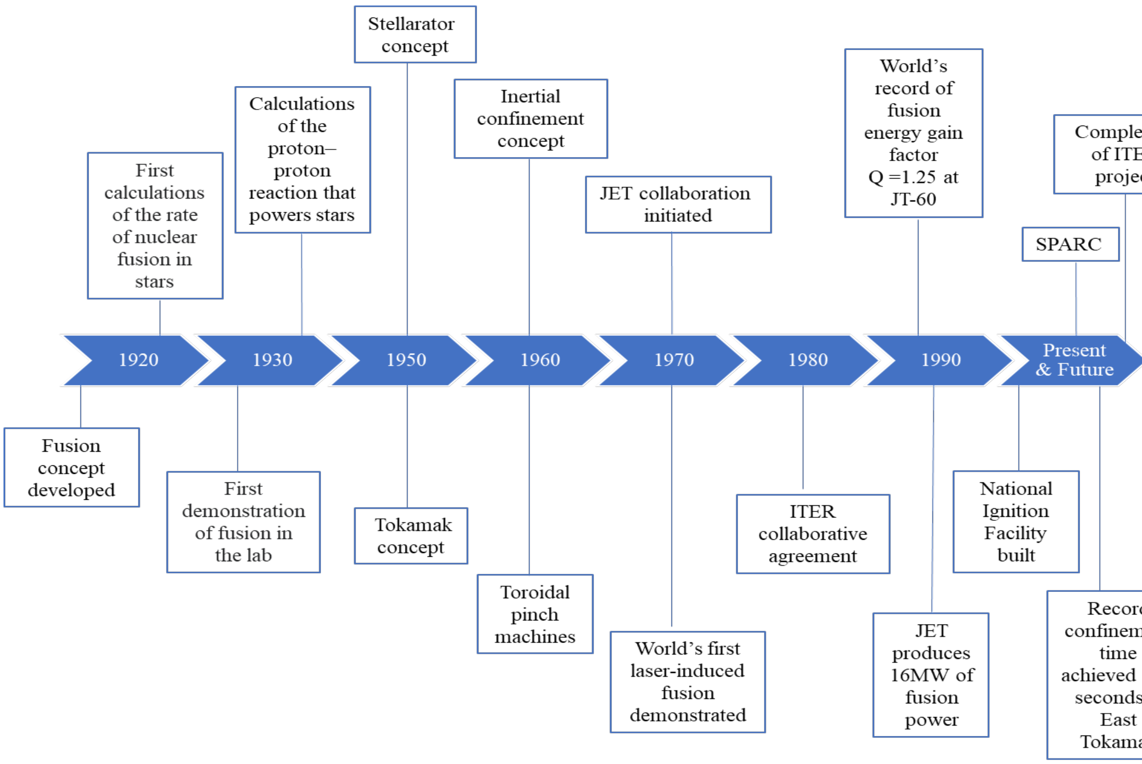


Figure 3. *A chronologically timeline of major development in fusion. The timeline is not exhaustive as numerous other advances were made throughout the years.*

4. A Deep Dive into The Fusion Energy

4.1. Why Fusion?

The Sun generates energy through nuclear fusion reactions by joining together two small atoms, such as hydrogen, to form a larger nucleus. It is the simplest natural fusion reactor. The process is driven by the Sun's mass, gravitational force and extremely high temperatures.[30] The benefits of this nuclear reaction include:

- Fusion works by turning small amounts of matter into vast amounts of energy. The nuclear fusion reaction is a clean technology, as no harmful waste is produced.
- Its major by-product is helium gas which is inert and non-toxic.
- Fusion reactions can be controlled and stopped within seconds as high temperature plasma and the external magnetic field confinement needed for a sustainable fusion reaction can be terminated at any point. As a result fusion energy production is inherently safe.
- Its non-polluting as no greenhouse gases or carbon dioxide are being produced in the process. It is a carbon-free energy source.

- An extremely small amount of fuel, a few grams, could produce megawatts of electricity per 1000 seconds. For example, fusion reactions require about six orders of magnitude ($\sim10^6$) less fuel compared with chemical energy sources (coal, oil, etc.).[31]
- Enormous energy output may be generated from fusion processes, making this an extraordinary and highly sought-after energy producing solution.
- The fusion reaction is continuous, and no energy storage strategies are needed.
- With minimal proliferation risks, nominal land, and water use, fusion could be easily implemented and accepted by public environmental advocates. Fusion power plants would have a limited negative environmental impact when compared with other renewable energy resources.

4.2. The Fuel - Hydrogen

Hydrogen (H), the fuel needed for a fusion reaction, is the most common and abundant element in the universe. Hydrogen is the lightest element ofthe periodic table. Its atomic number is 1 and the atomic mass is 1.008 amu.

Hydrogen has tree (3) naturally occurring isotopes: protium, deuterium and tritium (***Figure 3***). All three isotopes have the same number of protons and electrons, but different numbers of neutrons. Protium has no neutrons, deuterium has 1 neutron and tritium has 2 neutrons. Protium (P) and deuterium (D) are both stable isotopes while tritium is not. Tritium (T), the radioactive isotope of hydrogen, has a half-life of 12.3 years, with a loss of approximatively 5.5% per year. Tritium radioactively decays to helium-3. Hydrogen isotopes have been used in the medical field, nuclear energy, and defense missions.[32,33] Deuterium ca be used in fission reactors, neutron scattering, or as an isotope tracking marker in numerous chemical reactions.[34] Tritium is a critical component of nuclear weapons, fusion reactors, and self-illuminating light sources.[32-35]

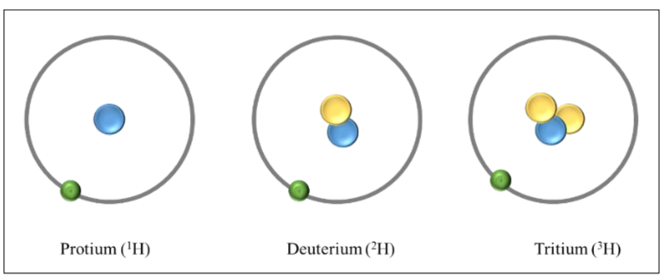


Figure 4. Hydrogen isotopes.

For fusion processes to be viable, an optimum energy balance must be achieved. The energy balance in these processes, such as output/input energy, determine which nuclei are the best candidates for the fusion reactions. Typically, the highest energy balance is obtained when lighter elements fuse together. Heavier elements can also be used, however. Output energy decreases as the mass of the nuclei increases. If elements heavier than iron are used, the energy balance is negative. This means the input energy is higher than the output energy.

When hydrogen nuclei fuse together during fusion reactions, a large amount of energy is released, along with byproducts such as helium and neutrons. These reactions typically produce weights that are less than the parent nuclei. The difference between the sum mass of the parent nuclei and the sum mass of the products is called the mass defect. The loss of mass in a fusion nuclear reaction is converted into energy, based on Albert Einstein's relation between energy and mass: $E = mc^2$. The most favorable fusion reactions include:[36]

$D + T \rightarrow {}^4He + n + 17.6MeV$ (1)

$D + D \rightarrow T + H + 3.98MeV$ (2)

$D + D \rightarrow {}^3He + n + 3.25MeV$ (3)

$T + T \rightarrow {}^4He + 2n + 11.3MeV$ (4)

While there are a number of potential fusion reactions, the most energetically feasible fusion reaction is between deuterium (D) and tritium (T) as the cross sections for their occurrence are high.[37] . This particular fuel mixture could reach fusion conditions at lower temperatures and generate the maximum amount of energy than any other system (***Figure 5***).[38] Moreover, the amount of energy generated per nucleon (neutron or proton) for the same mass of fuel, is significantly greater in a fusion reaction than in a fission reaction.

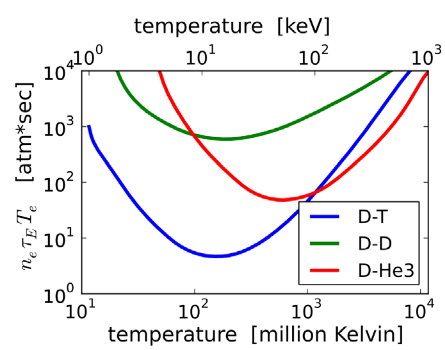


Figure 5. The fusion triple product condition for three fusion reactions.[38]

The deuterium fuel used in this fusion reaction is unlimited. Deuterium is abundant in nature and can be supplied from ocean waters. Approximatively 33 grams of deuterium could be collected from cubic meter of water. The estimated availability in Earth's ocean is $5*10^{16}$ kg which makes it accessible for billions of years.

Tritium, the other fuel needed in fusion reactions, doesn't occur naturally and is very limited in nature. As a result, it needs to be produced or bred internally within the fusion reactor. Tritium be can be easily produced from lithium. Lithium is a highly abundant metal on Earth. Tritium can be produced when lithium is being bombarded with neutrons as follows:

$${}^6Li + n \rightarrow {}^4He + T + 4.8\ MeV \quad (6)$$

Tritium is produced in what is called a blanket region. The major functions of the blanket region are to (a) efficiently capture the neutrons and energy produced by fusion reactions, (b) transfer heat to a coolant for electricity generation, and (c) create and extract fresh tritium fuel (by utilizing nuclear transmutation reactions with lithium-containing liquid or solid materials) to enable continuous operation of the fusion energy system.[39] The process doesn't pose any safety or health risks, and can be used to produce necessary fuel within the containment vessel. It is important to note that the amount of tritium needed in a fusion reaction is extremely low. Current lithium reserves could supply the world's energy demands for thousands of years.

Another potentially feasible fusion reaction is based on the reactions between deuterium and helium-3 (reaction 7):

$$D + {}^{3}He \rightarrow {}^{4}He + H + 18.3\ MeV \qquad (7)$$

In this case, the output energy is highly advantageous, generating 18.3 MeV of energy. No neutrons are initially being produced in this reaction. Nevertheless, the subsequent D+D reaction does generate neutrons. Moreover, the input energy needed for the reaction to take place is higher than D+T reaction. This results in an energy balance that is less effective. The helium-3 fuel used in this reaction is also extremely rare on Earth however. Helium-3 is 100 million times more abundant on the Moon. If efficient mining strategies of helium-3 from the Moon are developed, one could see their use in fusion reactions in the future.

Ultimately the fusion reactions between D and T producing helium and a neutron are universally accepted as the ideal fusion reaction (***Figure 6,*** Reaction 1). As expected, this still is not a trivial process as high temperatures that are ten times higher than the temperature at the core of the Sun must be achieved for the fusion reaction to take place.

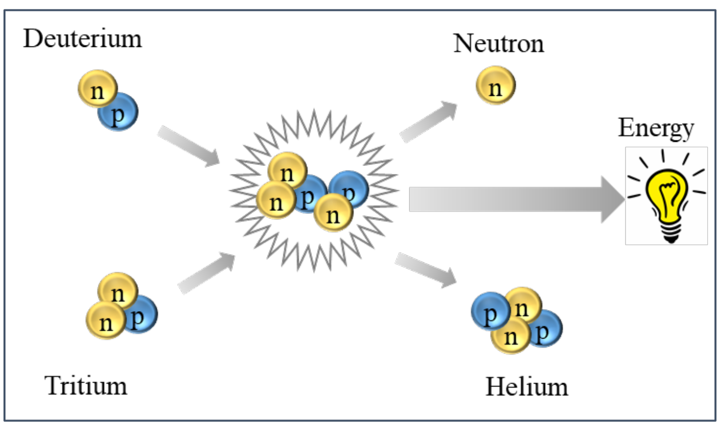


Figure 6. Fusion reaction between deuterium and tritium.

4.3. Plasma

Fusion reactions take place at temperatures in excess of 100,000,000K = 10KeV. Typically, at temperatures higher than 5,000K, matter becomes plasma. Once these enormous temperatures are reached, electrons are stripped from hydrogen atoms producing plasma, which is a collection of negatively charged electrons, positively charged nuclei (protons) and neutral atoms. Plasma is electrically conductive and can be manipulated, controlled and confined by electric and magnetic fields.

Ionized particles carry a charge. Electrically charged particles repel each other. For a fusion reaction to occur, these charged particles must be close enough to overcome inherent repulsive electrostatic forces. Given that both nuclei are positively charged and most likely repel each other, enormous energy and pressure are required to overcome these repulsive forces. The fusion process will depend on scientists' ability to create perfect conditions for (a) temperatures and (b) confinement for efficient collision of these charged particles. These nuclei must be confined and have a temperature over 100 million degrees for a fusion reaction to take place. The highest probability of a D-T fusion reaction can be achieved when the nuclei have kinetic energies of approximatively 100 Kev.[40] Once distance and temperature conditions are met, the strong nuclear force that binds quarks (protons and neutrons) together takes over, bringing the charged particles together. The particles' velocities and probability of collision increases with the temperature. The conditions needed for self-sustaining plasma are: a sufficient plasma density of 10^{20} nuclei/m^3, be sustained at high enough temperature of 15-20 KeV, maintaining its heat for a sufficient time (2 seconds), and sustained fusion plasma that follows Lawson Criterion - output energy is higher than input energy and loss.[37-42]

4.3.1. Achieving High Temperatures of Plasma for Fusion

Fusion must occur at very high temperatures to generate plasma. The fusion reaction must be continuous and, like stars, must heat itself to millions of degrees Kelvin. Plasma heating is typically achieved when an electric current pass through a conductive plasma. The origin of this heating is due to the Joule effect, or resistive or ohmic heating. Temperatures of up to 10 million degrees can only be achieved through the Joule effect. As temperatures increase, plasma resistance decreases, limiting the efficiency of the process. Achieving and sustaining the high temperatures necessary for a steady state fusion reaction require the use of external heating processes. Two different heating strategies have been developed: high frequency electromagnetic wave heating and neutral-beam injection heating.

High frequency electromagnetic wave heating relies on using the unique characteristics of radiofrequency (RF) energy or microwave energy to heat plasma. This antenna-type heating approach relies on the transferring of heat to plasma via electromagnetic waves at appropriate frequencies. This is because ionized particles can sustain and support the propagation of RF energy. At resonance, when the frequency of the electromagnetic wave matches the frequency at which a nucleus rotates around a magnetic field line, energy is transferred to the nucleus. The substantial heating of plasma with RF waves was demonstrated for the first time in 1960 by Stix and collaborators in the B-65 Stellarator.[41] In 1985, the heating of a fusion reactor to relevant temperatures was first demonstrated on the Princeton Large Torus.[42] RF heating of plasma has since drawn considerable interest. Heat can be applied to specific targeted areas without affecting other nearby areas.[32,34,43] The use of RF energy to heat plasma is also non-intrusive, making it a preferable method.

Heating can also be achieved by the injection of a neutral beam into the plasma. The collision between these particles and plasma leads to temperature rises. Two different technologies have emerged: ion cyclotron resonance heating and electron cyclotron resonance heating. Charged particles are neutralized before introduction into the plasma. A high-intensity beam of electromagnetic radiation with a frequency of 40 to 55 MHz is used in the ion cyclotron resonance heating. The electron cyclotron resonance heating requires very high frequencies, tens to hundreds of gigahertz, which are generated by free-electron lasers and gyrotron tubes.[44] The electron cyclotron resonance heating system is often preferred over the ion cyclotron resonance heating as (a) it can be incorporated to generate heat at specific locations in the plasma, eliminating the instability issues that cool the plasma and (b) could be transmitted through air, simplifying the design and allowing the source to be far from the plasma simplifying maintenance.

4.3.2. Achieving Confinement of Plasma for Fusion Energy

Temperatures in the millions of degrees are required to generate fusion energy on Earth. Unfortunately, no material can withstand these temperatures. In order to circumvent these limitations, the unique properties of plasma must be interrogated and exploited. Turbulent mixtures of ions and free electrons, plasma, must be stabilized and in a state of equilibrium. Plasma must also be confined as if its drifting to the reactor walls it cools instantly.

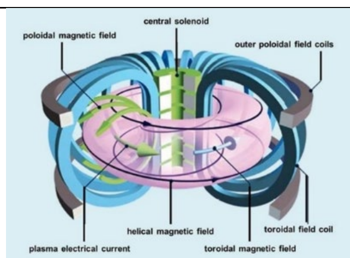
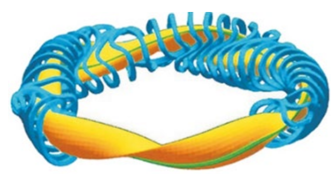
Plasma conducts electricity as its constituents are charged particles. Movement of ionized particles generates localized magnetic fields that can be controlled and manipulated by external magnetic fields. Two different strategies have emerged to confine and control the movement of the charged particles at extraneous temperatures: magnetic confinement (or Tokamak) and inertial laser confinement. Confinement refers to all of the conditions necessary to keep a plasma dense and hot enough to undergo fusion.

4.3.2.1. Magnetic Confinement

Magnetic confinement refers to the process in which ionized particles are confined by magnetic fields. Magnetic fields generated by induced currents can be used to confine the plasma.[37] Charged particles, when exposed to a magnetic field, are deflected by the Lorentz. These forces oblige charged particles to move into circular orbits. The gyroscopic motion of the charged particles, electrons and ions, in the direction of the magnetic line of force, confines the particles away from the wall vessel. Speeds of approximatively 1,000 km/s were reported.[45] These speeds were obtained at the temperatures necessary to achieve fusion. Heat and energy are also transported along these fields. If a simple straight configuration is used, end losses are inevitable. Plasma end losses are typically eliminated by using a donut or torus design. This configuration was first introduced by Russian scientists in the 1960s. The donut shape or torus was coined the 'Tokamak' configuration. This is an acronym from Russian language for 'toroidal chamber with axial magnetic field'. Three different magnetic field coils efficiently confine the path of travel of charged plasma particles: the toroidal field coil, the central solenoid field coil and the poloidal field coils. All magnetic field components are needed to confine, shape and contain the plasma in a steady state at equilibrium. [46]

Tokamak was a major achievement in the field of nuclear fusion. It has led to additional advances such as the Stellarator. Stellarator operates on the same principle as Tokamak. It is based on the use of external magnets to confine plasma.[19] This design is based on a cumbersome spiraling ribbon that is more difficult to produce (Table 2). Nevertheless, once operational, a steady state plasma with limited magnetic disruptions is achieved.

Table 2. *Tokamak vs. Stellarator.*[Error! Bookmark not defined., 47]

Tokamak	Stellarator
	
• Powerful electromagnetic fields confine and heat plasma inside a tokamak; • A strong toroidal current is induced by a central solenoid; • Excellent plasma confinement; • Requires the continuous flow of an electric current in a donut-shaped plasma; steady-state operation require strong current drive; • Most advanced confinement configuration.	• Complex spiraling ribbon shape design produces high-density plasma that's symmetrical and more stable than a tokamak's, allowing the reactor to run for long periods of time; • Weak, self-generated toroidal current; • Challenging geometry makes it complicated to build and extremely sensitive to imperfect conditions; • Requires careful optimization to ensure sufficiently good confinement properties; • It is inherently in steady state, and the likelihood of exciting major disruptions is much lower. • Excellent plasma confinement to be proven.

Magnetically confined plasmas have achieved temperatures today that are 10 times hotter than the core of our Sun at various facilities across the world. The DIII-D National Fusion Facility, operated by General Atomics for the U.S. Department of Energy, is one of the few facilities that uses a toroidal (donut-shaped) chamber surrounded by powerful electromagnets to confine high-temperature plasmas.[48] The National Spherical Torus Experiment Upgrade (NSTX-U) is a fusion facility built by Princeton Plasma Physics Laboratory (PPPL). It uses a tokamak design that was recently upgraded, making it the most powerful in the world.

4.3.2.2. Inertial Laser Confinement

Since 1970, a radically different confinement approach was proposed - inertial laser confinement. This new strategy doesn't involve the use of a magnetic confinement, but extremely powerful lasers to generate fusion. It is based on the inertia generated in imploding matter. The inertial laser confinement approach uses lasers to compress and heat fuel pellets containing hydrogen and tritium at high rates to generate fusion. This process is based on four steps (**Figure 6**):

(a) **Deliver laser energy**: Energy is delivered to the external fuel pellet's shell by high-energy laser beams;
(b) **Plasma generation:** The outer layer of fuel is getting hot generating a plasma outer layer;
(c) **Blow-off and fuel compression:** The heated outside shell shatters outward generating inward forces (shock-waves) that compress the fuel pellet. This process is based on Newton's third law of motion. Newton's third law states that for every action force, there is an equal and opposite reaction force.
(d) **Ignition and fusion reaction:** If shock waves are powerful enough, the fuel pellet is compressed and heated to sufficient temperature to accomplish fusion reactions.

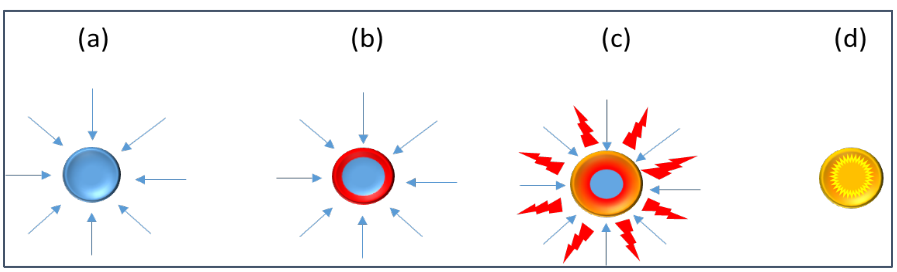


Figure 7. *Schematic of the inertial laser confinement.*[49]

The amount of fuel needed to achieve fusion is extremely small. The size of a 10 mg of fuel is around the size of a pinhead, making this a highly feasible approach. The laser-plasma instabilities often hinder the required heat and densities needed for the fusion reaction. The high cost and complexity of laser drivers limits the large-scale implementation of this strategy.

The National Ignition Facility (NIF) is the most advanced facility of its kind in US. It specifically focuses on achieving inertial confinement fusion. It has been reported that two megajoules of light energy (the energy consumed by 20,000 100-watt light bulbs in one second) can be delivered in 16 nanoseconds.[49]

4.4. Materials and Fusion

Nature provides us with an extraordinary assortment of materials that can meet many of our demands regarding performance, cost and availability. Material scientists have also designed and created new materials with improved properties and performance. This has resulted in outstanding technological achievements and successes. Surprisingly, however, materials are still the limiting factor in many industries. Stronger and more robust materials that are virtually unaffected by stringent thermal, radioactive and chemical environments are still needed in the foreseeable future.

Development of materials for fusion energy poses new challenges as nearly all components and materials must withstand aggressive operational and experimental parameters such as radiation, high temperatures, stress and pressures. Resilience against high heat fluxes under steady state conditions, plasma particle fluxes, and fluxes of high-energy neutrons must be taken into consideration when designing and developing new materials. Materials must be thermally conductive, resilient regarding corrosion and fatigue damage caused by neutron resistance, or oxidation resistant during accidental air ingress. Neutron-induced effects, e.g., transmutation adding to embrittlement, hydrogen isotope retention, and changes to thermomechanical properties, are also crucial to material performance. High thermal stress and high strength or high-fracture toughness at elevated temperatures are critical parameters and challenges that require material innovation breakthroughs. The field is rich with opportunities toward developing innovative complex hierarchical composites, complex alloys, adaptive-and self-healing materials, and hybrid liquid/solid systems to incorporate in fusion reactors.[50]

The most attractive materials for fusion energy applications are typically high z materials, as low z materials have low melting points and high erosion rates. Refractory metals, such as tungsten (W), tantalum (Ta), niobium (Nb), rhenium (Re), molybdenum (Mo), are explored as plasma facing materials as they have favorable properties. Tungsten and tungsten-based alloys for example have high melting points above 2000 ^{o}C. Additionally, they have high strength, high thermal conductivity, low tritium inventory, low thermal expansion, low activation, low erosion rate and high-temperature yield strength.[51] Their recrystallization and brittle-to-ductile transition must be overcoming before successful incorporation and implementation.

There are several candidates for investigation including ferritic martensitic steel, and vanadium-based alloys. High entropy alloys such as V-Nb-Mo-Ta-W, Fe-Ni-Mn-Cr and Ni-Co-Fe-Cr systems, and castable nanostructured alloys such as MAX-phase materials (Ti_3SiC_2) are potential candidates.[50,52] Vanadium alloys are superior to ferritic/martensitic steels as they display greater high-temperature performance.[53] There are also reports that vanadium alloys have low activation materials that are also compatible with liquid lithium. However, production of vanadium alloys is still in its infancy.

Low z materials, such as beryllium or carbon, are also attractive due to their low sputtering yield. SiC/SiC fiber-reinforced SiC composites have been investigated as a viable first wall material due to their excellent high-temperature strength.[54] Beryllium was also explored as a candidate for the first wall. However, its low melting temperature, swelling during transient loads and toxicity must be taken into consideration.

Carbon based materials have been also shown promising results. Graphite, a crystalline form of carbon with a hexagonal structure, was found to increase plasma temperature dramatically due to its efficient radiation properties.[55] High-quality diamond films have been produced that have low loss and high thermal conductivity.[56] Diamond has also been suggested as an alternative to graphitic carbon as a possible divertor material.[57] Its exceptional thermal conductivity is favorable for high thermal loads and its strong bonding should decrease its susceptibility to chemical erosion by hydrogen. Protective nano- and micro-scale coatings of diamond materials on Mo, Si and graphite have shown successes.[58]

Liquid metals have been explored as a plasma-facing interface material due to their self-healing/renewable ability to adapt to conditions in a fusion energy reactor. They can transfer heat from the system while maintaining the structural integrity of the walls and minimizing the tritium retention.[59] Lithium, gallium, and tin are the most promising plasma facing components liquid metals as these Extensive research has been focused on using liquid lithium (Li) or lithium-based systems (Li-Mo, Li-Sn), in confinement devices by Russia, U.S. and China.[60,61,62] The Lithium Tokamak Experiment, for example, the only device with a full liquid Li wall, has extremely encouraging results on confinement.[63] Li pellets and Li spray in DIII-D demonstrate enhanced confinement correlated with recycling.[64] The biggest concern when handling Li is its flammability. Liquid gallium was employed for power removal as it possesses excellent heat transfer properties. While promising advances have been made in these areas, additional studies regarding tritium handling and recovery, temperature control, chemical compatibilities between systems, and materials instabilities, reliability, successful integration of systems in a safe manner must be addressed when using liquid metals technologies in the fusion power plants.

The widespread adoption of fusion energy technologies relies on scientist' ability to accelerate materials discoveries. Materials-By-Design or Materials Genome Initiative are just a few multi-agency initiatives designed to support and fund U.S. institution in their quest to "discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost".[65] Scientists currently exploring production of materials-by-design for fusion energy through additive manufacturing technologies. Additive Manufacturing (AM), or 3D printing, is a unique technology in which structurally complex objects can be easily manufactured. AM methods have several advantages over traditional manufacturing techniques. AM offers "design freedom" that allows the creation of structurally complex objects that were once unbuildable. With AM it is possible to create functional parts without the need for assembly. AM reduces the amount of generated waste and often requires a minimal use of harmful chemicals. It also eliminates the need for additional etching and cleaning steps.

5. Conclusions and Outlook

If realized on Earth, nuclear fusion could solve global energy demands for generations to come. Fusion is an environmentally friendly clean energy resource that produces no greenhouse gases. Limitless amounts of fuel are available for fusion reactions. Deuterium can be extracted from oceans, while tritium can be easily bred from abundant lithium resources. Fusion reactions are fundamentally safe and can be stopped on command, eliminating the risk of uncontrollable processes.

For decades, scientists have been exploring multifaceted and comprehensive strategies for the production and development of a controlled nuclear fusion reaction in the laboratory. Achieving fusion in a laboratory setting, however, is not trivial. Fusion can only occur at extremely high temperatures (10-15 million K) making it difficult to achieve and contain. It is a very complex process that requires the use of numerous devices, technologies, materials, and interfaces. These include magnetic field coils, transformers, cooling equipment, blanket modules, divertors, vessels, beam injectors, etc. The integration of these components and an integrated operation of all technologies promises to generate 500 MW of fusion power from 50 MW of input heating power. This is to be demonstrated in the most advanced prototype – ITER – in 2035. A typical fusion power plant will need to satisfy Lawson criterion (energy output > energy input), breed tritium and collect heat to drive turbines to actually make electricity and put it on the grid. While extraordinary advances have been made in these fields to date, the energy required to make fusion work is greater than the output energy. Broad implementation of innovative technological advances is still required to realize fusion on Earth meet Lawson criterion.

The entire fusion energy and plasma science community has recently come together and developed a long-range plan for the U.S. to accelerate the delivery of fusion energy, and advance plasma science. This consensus vision has culminated in the creation of the Powering the Future Fusion & Plasmas Report.[66] This report was recently approved by the Fusion Energy Science Advisory Committee (FESAC).[67] The year-long study identified new opportunities and developed guidance for prioritization including:[66]

(a) The Fusion Science and Technology (FST) scientific community should establish the scientific and technical basis for a fusion pilot plant by 2040s. This fusion plant, if realized, will sustain a burning plasma, integrate and operate materials and technologies in extreme conditions and harness fusion power.

(b) The Plasma Science and Technology (PST) area should advance fundamental understanding of plasma and translate those advances into applications that benefit society. These advancements would expand our understanding the Plasma Universe, strengthening of the matter/new regime foundations, and the creation of create transformative technologies.

Government and private industry from around the world have made substantial capital investments in their quests to bring fusion to fruition. These efforts must continue to accelerate progress. Public-private partnerships like ITER at the national and international level are highly encouraged as they may lead to the rapid development of a commercially viable fusion energy. Although much research is still needed in this area, once the fusion process can be efficiently replicated on Earth, it could provide limitless, clean and sustainable energy to power the world.

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