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Nuclear Fusion: Holy Grail of Energy

Quamrul Haider

Abstract

The declining reserves of fossil fuels and their detrimental effects on the environment have thrust nuclear power based on fission reaction into the limelight as a promising option to energy-starved economies around the world. However, the 1986 Chernobyl and 2011 Fukushima accidents have heightened our fears about nuclear technology's ability to provide a safe way of generating clean power. There is another kind of nuclear energy that has been powering the Sun and stars since their formation. It is nuclear fusion—a process in which two lighter nuclei, typically isotopes of hydrogen, combine together under conditions of extreme pressure and temperature to form a heavier nucleus. In this chapter, harnessing the energy produced in nuclear fusion reaction in a laboratory environment is discussed. Various research programs dedicated to building fusion reactors are also discussed. Emphasis is given on overcoming some of the technological challenges, such as surmounting the Coulomb barrier, confining the plasma, and achieving the “ignition” temperature for fusion.

Keywords: nuclear fission and fusion, fission and fusion reactors, fusion in the Sun, fusion on Earth, cold fusion, Coulomb barrier, fusion “ignition” temperature, Lawson criterion, Debye length, plasma confinement, magnetic and inertial confinements, tokamak, stellarators, fusion torch

1. Introduction

The 1930s were heady times for nuclear physics. A “hit parade” of discoveries gave us new insights into the properties of the nucleus. The means of unlocking enormous amount of energy stored inside a nucleus seemed at hand. Finally, the discovery of nuclear fission in 1938 ushered in a new era in the history of mankind—the nuclear age [1].

Nuclear energy is a technologically proven nonfossil energy source that made significant contribution to the world's energy supply in the past 6 decades. There are two nuclear processes in which enormous amount of energy is released from nuclear bonds between the particles within the nucleus. They are nuclear fission and nuclear fusion.

2. Nuclear fission

The importance of nuclear fission for the production of energy is obvious. In fission reactions, a heavy nucleus is split into two lighter fragments and two or three

neutrons. About 180 MeV of energy is produced in the fission of an actinide to one of its most probable daughter pairs. This means that 1 kg of uranium (^{235}U) is capable of producing enough energy to keep a 100-Watt light bulb running for about 25,000 years [2].

2.1 Fission reactors

All nuclear power plants in operation today rely on controlled fission of the isotopes of uranium and plutonium [3]. The reactor functions primarily as an exotic heat source to turn water into pressurized steam. Only the source of heat energy differs—nuclear power plants use fissile radioactive nucleus, while nonnuclear power plants use fossil fuel. The rest of the power train is the same. The steam turns the turbine blades, the blades generate mechanical energy, the energy runs the generator, and the generator produces electricity. The major improvement is the elimination of the combustion products of fossil fuels—the greenhouse gases, which have destroyed our environment beyond repair.

Because of its abundance in nature, most nuclear reactors use uranium as fuel. Natural uranium contains 0.7% of the fissile ^{235}U ; the rest is non-fissile ^{238}U . When ^{235}U is bombarded with a slow neutron, it captures the neutron to form ^{236}U , which undergoes fission producing two lighter fragments and releases energy together with two or three neutrons. The neutrons produced in the reaction cause more fission resulting in a self-sustaining chain reaction. A reactor is considered safe when a self-sustained chain reaction is maintained with exactly one neutron from each fission inducing yet another fission reaction.

2.2 Problems and concerns with fission reactors

Although fission-based nuclear reactors generate huge amounts of electricity with zero greenhouse gas emissions, and thus was hailed as a solution not only to global warming but also to global energy needs, nuclear energy is now seen by many, and with good reasons, as the misbegotten stepchild of nuclear weapons programs. Besides, it is by no means certain that the safety systems designed to shut down the reactor in the event of a runaway reaction are 100% foolproof and will work as designed. Another area of great concern is the hazards associated with the disposal of highly radioactive waste products.

What has raised our fear in regard to nuclear power more than anything else are the accidents at Chernobyl in 1986 and Fukushima in 2011. They were a sobering reminder of what we can expect from an accident due to catastrophic reactor failure or human errors. The Fukushima disaster in particular has shattered the zero risk myth of power reactors and heightened our concern about the invisibility of the added lethal component, nuclear radiation. Consequently, they have spurred our interest in the other source of nuclear energy—fusion.

3. Nuclear fusion

Nuclear fusion is the process in which two lighter nuclei, typically isotopes of hydrogen, combine together under conditions of extreme pressure and temperature to form a heavier nucleus, resulting in the release of enormous amount of energy. The fusion of four protons to form the helium nucleus ^4He , two positrons, and two neutrinos, for example, generates about 27 MeV of energy.

In the 1930s, scientists, particularly Hans Bethe, discovered that it is fusion that has been powering the Sun and stars since their formation [4]. A “fusion reactor” buried deep in the Sun’s interior produces in one heartbeat the energy of 100 billion nuclear bombs. Beginning in the 1940s, researchers began to look for ways to initiate and control fusion reactions to produce useful energy on Earth. We now have a very good understanding of how and under what conditions two nuclei can fuse together.

3.1 Fusion in the Sun

The fusion of hydrogen into helium in the Sun and other stars occurs in three stages. First, two ordinary hydrogen nuclei (^1H), which are actually just single protons, fuse to form an isotope of hydrogen called deuterium (^2H), which contains one proton and one neutron. A positron (e^+) and a neutrino (ν) are also produced. The positron is very quickly annihilated in the collision with an electron, and the neutrino travels right out of the Sun:



Once created, the deuterium fuses with yet another hydrogen nucleus to produce ^3He —an isotope of ^4He . At the same time, a high-energy photon, or γ ray, is produced. The reaction is



The final step in the reaction chain, which is called the proton-proton cycle, takes place when a second ^3He nucleus, created in the same way as the first, collides and fuses with another ^3He , forming ^4He and two protons. In symbols,



The net result of the proton-proton cycle is that four hydrogen nuclei combine to create one helium nucleus. The mass of the end product is 0.0475×10^{-27} kg less than the combined mass of the ^3He nuclei. This mass difference, known as mass defect in the parlance of nuclear physics, is converted into 26.7 MeV of energy as known from Einstein’s equation $E = mc^2$.

The proton-proton cycle is particularly slow—only one collision in about 10^{26} for the cycle to start. As the cycle proceeds, the Sun’s temperature rises, and eventually three ^4He nuclei combine to produce ^{12}C . Despite the slowness of the proton-proton cycle, it is the main source of energy for the Sun and for stars less massive than the Sun. The amount of energy released is enough to keep the Sun shining for billions of years.

Besides the proton-proton cycle, there is another important set of hydrogen-burning reactions called the carbon-nitrogen-oxygen (CNO) cycle that occurs at higher temperatures. Although CNO cycle contributes only a small amount to the Sun’s luminosity, it dominates in stars that are more massive than a few times the Sun’s mass. A star like Sirius with somewhat more than twice the mass of the Sun derives almost all of its energy from the CNO cycle.

4. Coulomb barrier

An obstacle called the Coulomb barrier caused by the strongly repulsive electrostatic forces between the positively charged nuclei prevents them from fusing

under normal circumstances. However, fusion can occur under conditions of extreme pressure and temperature. That is why fusion reaction is often termed as thermonuclear reaction.

Nuclei, which have positive charges, must collide at extremely high speeds to overcome the Coulomb barrier. The speed of particles in a gas is governed by the temperature. At the very center of the Sun and other stars, it is extremely hot and density is very high. For the Sun, the temperature is around 15 million degrees Celsius, and the central density is about 150 times that of water. Under such extreme conditions, electrons in an atom become completely detached from the atomic nucleus, thereby forming an ionized fluid called plasma—a “soup” of hot gas, with bare, positively charged atomic nuclei and negatively charged electrons whizzing about at extremely high speeds. The plasma as a mixture of positive ions (nuclei) and negative electrons is overall electrically neutral.

Without the high pressure of the overlying layers, the hot plasma at the solar core would simply explode into space, shutting off the nuclear reactions. The pressure, which is about 250 billion atmospheres at the Sun’s core, squeezes the nuclei so that they are within 1 fm (10^{-15} m) of each other. At this distance, the attractive strong nuclear force that binds protons and neutrons together in the nucleus becomes dominant and pulls the incoming particles together, causing them to fuse.

Additionally, massive gravitational force causes nuclei to be crowded together very densely. This means collisions occur very frequently, another requirement if a high fusion rate is to occur. A quick and crude calculation suggests that we need about 10^{38} collisions per second to keep the Sun going, while within the core we get about 10^{64} collisions per interactions per second, implying only one in 10^{26} collisions needs to be a successful fusion event.

5. Nuclear fusion on Earth

One of the major challenges in initiating a fusion reaction in a laboratory environment on Earth is to create conditions similar to that in the Sun—extremely high temperatures, perhaps more than 100 million degrees Celsius (equivalent to mean particle kinetic energies of ~ 10 keV) while simultaneously maintaining a high enough density for a long enough time so that the rate of fusion reactions will be large enough to generate the desired power.

5.1 “Ignition” temperature

We can estimate the minimum temperature required to initiate fusion by calculating the Coulomb barrier which opposes two protons approaching each other to fuse. With $e^2 = 1.44$ MeV-fm, where e is the charge of a proton, and $r = 1.0$ fm (separation between two protons), the height of the Coulomb barrier is

$$U = \frac{e^2}{r} = 1.44 \text{ MeV.} \quad (4)$$

The kinetic energy of the nuclei moving with a speed v is related to the temperature T by

$$\frac{1}{2}mv^2 = \frac{3}{2} k_B T, \quad (5)$$

where $k_B = 8.62 \times 10^{-11}$ MeV/K is the Boltzmann constant. By equating the average thermal energy to the Coulomb barrier height and solving for T gives a value for the temperature of around 10 billion Kelvin (K).

The above “back of the envelop” calculation, using classical physics, does not take into consideration the quantum effect of tunneling, which predicts there will be a small probability that the Coulomb barrier will be overcome by nuclei tunneling through it. The probability P of such an event happening is

$$P \propto \exp \left(-\frac{Z_1 Z_2 \alpha c}{v} \right), \quad (6)$$

where Z_1 and Z_2 are the atomic numbers of the interacting particles, $\alpha = 1/137$ is the fine structure constant, and v is the relative velocity of the colliding nuclei. Using the classical turning point r_0 and de Broglie wavelength $\lambda = h/p = h/mv$, the above expression can be written as

$$P \propto \exp \left(-\frac{r_0}{\lambda} \right). \quad (7)$$

Thus, large values of v (high energies), or small λ , favor a fusion reaction.

Taking into account the tunneling probability, we can now estimate the temperature for fusion to occur. In terms of de Broglie wavelength, the kinetic energy is

$$K = \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2}. \quad (8)$$

If we require that the nuclei must be closer than the de Broglie wavelength for tunneling to take over and the nuclei to fuse, then the Coulomb barrier is given by

$$\frac{e^2}{\lambda} = \frac{h^2}{2m\lambda^2} \rightarrow \lambda = \frac{h^2}{2me^2}. \quad (9)$$

If we use this wavelength as the distance of closest approach to calculate the temperature, we obtain

$$\frac{3}{2} k_B T = \frac{e^2}{\lambda} = \frac{2me^4}{h^2}. \quad (10)$$

Solving for the temperature, we get

$$T = \frac{4me^4}{3h^2 k_B} = \frac{mc^2 \alpha^2}{3\pi^2 k_B}. \quad (11)$$

For two hydrogen nuclei ($mc^2 = 940$ MeV), this gives a temperature of about 20 million Kelvin.

6. Fusion reactor

Since the 1950s, scientists have been working tirelessly to develop a reactor in order to harness the nearly inexhaustible energy produced during fusion [5]. The goals of fusion research at present include the following:

1. To achieve the required temperature to ignite the fusion reaction.
2. To keep the plasma together at this temperature long enough to get useful amounts of energy out of the thermonuclear fusion reactions.
3. To obtain more energy from the thermonuclear reactions than is used to heat the plasma to the ignition temperature.

To date, much headway has been made toward achieving these goals.

6.1 Fuel

Just like the Sun, the fuel for a fusion reactor is hydrogen, the most abundant element in the Universe. But without the benefit of gravitational force that is at work in the Sun, achieving fusion on Earth requires a different approach. The simplest reaction in which enormous amount of energy will be released is the fusion of the hydrogen isotopes deuterium (^2H) and tritium (^3H) producing ^4He and a neutron. For the sake of brevity, we will use the notation d and t for deuterium and tritium, respectively.

Deuterium is found aplenty in ocean water, enough to last for billions of years. This makes it an attractive source of alternative energy relative to other sources of energy. Naturally occurring tritium, on the other hand, is extremely rare. It is radioactive with a half-life of around 12 years. Trace quantities of tritium can be found in cosmic rays. Nevertheless, it can be produced inside a reactor by neutron (n) activation of lithium (Li), the other raw material for fusion found in brines, minerals, and clays. Because of the abundance of fusion fuel, the amount of energy that can be released in controlled fusion reactions is virtually unlimited.

For d-t reaction, we must first create the tritium from either flavor of lithium:



or



The next step in the reaction is



The neutrons generated from the d-t fusion can be used to bombard lithium to produce helium and tritium, thereby starting a controlled, sustainable chain reaction.

The mass of the resulting helium atom and neutron is not the exact sum of the masses of deuterium and tritium. Once again, because of mass defect, each lithium nucleus converted to tritium will end up yielding about 18 MeV of thermal energy. Compared to fission, where each split of uranium releases about 200 MeV of energy, it might appear that the energy released during fusion is rather small. The discrepancy in the energies lies in the number of nucleons involved in the reactions—more than 200 for fission and 5 for fusion. On a per nucleon basis, fusion releases $18/5 = 3.6$ MeV, while fission releases $200/236 = 0.85$ MeV. So, fusion wins hands down, by greater than a factor of 4.

The other fusion scheme for which the required fuel (^4He) will be produced is $\text{d} + \text{d} \rightarrow ^4\text{He}$. Another reaction, $^2\text{H} + ^3\text{He} \rightarrow ^4\text{He} + p$, is an example of a fusion

reaction that releases its energy entirely in the form of charged particles, rather than neutrons, thereby offering the possibility, at least in principle, of direct conversion of fusion energy into electrical energy. However, the cross sections and reaction rates for both the reactions are as much as a factor of 10 lower than the d-t reaction. Moreover, because of the higher Coulomb barrier (~ 2.88 MeV), the ignition temperatures required for $^2\text{H} + ^3\text{He}$ reaction are much higher than those of d-t fusion.

An interesting fusion reaction is a proton colliding with boron (B). The proton fuses with ^{11}B to form ^{12}C which immediately decays into three alpha (^4He nucleus) particles. A total energy of 8.7 MeV is released in the form of kinetic energy of the alpha particles. Since it is relatively easy to control the energy of the proton with today's accelerator technology, this fusion reaction can be easily initiated without involving other interaction channels.

6.2 Conditions for fusion reaction

In order to attain the temperature for fusion to occur, the plasma has to meet some conditions. They are Lawson criterion and Debye length.

6.2.1 Lawson criterion

In addition to providing a sufficiently high temperature to enable the particles to overcome the Coulomb barrier, a critical density of the ions in the plasma must be maintained to make the probability of fusion high enough to achieve a net yield of energy from the reaction. The condition which must be met for a yield of more energy than is required for the heating of the plasma is stated in terms of the product of the plasma density (n_d) and confinement time (τ). The product has to satisfy the inequality:

$$n_d \tau \geq 3 \times 10^{20} \text{ s/m}^3. \quad (15)$$

This relation is called the Lawson criterion [6]. Researchers sometimes use the triple product of n_d , τ , and the plasma temperature T . Called the *fusion product*, the condition for fusion to take place is

$$n_d \tau T \geq 5 \times 10^{21} \text{ s} \cdot \text{keV/m}^3. \quad (16)$$

To summarize, three main conditions are necessary for nuclear fusion:

1. The temperature must be hot enough to allow the ions to overcome the Coulomb barrier and fuse together. This requires a temperature of at least 100 million degrees Celsius.
2. The ions have to be confined together in close proximity to allow them to fuse. A suitable ion density is $2 - 3 \times 10^{20}$ ions/m³.
3. The ions must be held together in close proximity at high temperature long enough to avoid plasma cooling.

At higher densities, charged particles in the plasma moving at high speeds may give rise to bremsstrahlung—radiation given off by a charged particle (most often an electron) due to its acceleration caused by an electric field of another charged particle (most often a proton or an atomic nucleus). Bremsstrahlung could become so dominant that all the energy in the plasma may radiate away. Other radiation

losses, including synchrotron radiation from charged particles orbiting about magnetic fields would be negligible. A fusion reactor, therefore, has to be operated at a temperature where the power gain from fusion would exceed the bremsstrahlung losses.

6.2.2 Debye length

A parameter that determines the electrostatic properties of a plasma is called the Debye length L_D [7]:

$$L_D \propto \sqrt{\frac{k_B T}{n_d}}. \quad (17)$$

It is a length scale over which electrons screen out electric fields in the plasma. In other words, it is the distance over which significant charge separation can occur and how far its electrostatic effect persists. For distances greater than the Debye length, the energy of the particles in the plasma balances the electrostatic potential energy.

Using $n_d = 10^{28}$ particles/m³, the Debye length for a 10 keV plasma is of the order of 10 nm, and the number of particles in a volume of the plasma of one Debye length is about 10^4 . For a more rarefied plasma, say $n_d = 10^{22}$ particles/m³, $L_D = 10 \mu\text{m}$, and the number of particles in a volume of dimension of one Debye length is 10^7 . In either of these two extreme cases, there are two basic properties: the physical size of the plasma is far larger than the Debye length, and there are many particles in a spherical volume of radius equal to one Debye length. They are these two properties that describe the hot thermonuclear fuel.

7. Plasma confinement

Just like a conventional power plant, a fusion power plant will use the energy released during fusion reaction to produce steam and then generate electricity by way of turbines and generators. But as noted in the above discussions, it is hard to harness the energy in a laboratory environment.

Each fusion reaction is characterized by a specific ignition temperature, which must be surpassed before the reaction can occur. In stars, which are made of plasma, fusion takes place because of immense gravitational forces and extreme temperatures. Trying to create similar conditions here on Earth has required fundamental advances in a number of fields, from quantum physics to materials science. Scientists and engineers have made enough progress over the past half century, especially since the 1990s, so that a fusion reactor able to generate more power than it takes to operate can be built. Supercomputing has helped enormously, allowing researchers to precisely model the behavior of plasma under different conditions.

One of the major requirements in the development of a fusion reactor is the actual realization of the ignition temperature of d-t reaction, which is 100 million degrees Celsius. Once all the conditions are realized, the challenge to contain and control the staggering levels of heat in the plasma is formidable. That is because the plasma must not only be heated to a temperature of at least 100 million degrees Celsius, but the energy must also be confined within the plasma without being carried to walls of the container for times long enough for the relatively infrequent fusion events to occur. Otherwise, the plasma will exchange energy with the walls, cool itself down, and melt the container.

Many techniques have been developed, but the two main experimental approaches that seem capable of doing this task are magnetic confinement and inertial confinement.

7.1 Magnetic confinement

This method uses strong magnetic fields to contain the hot plasma and prevent it from coming into contact with the reactor walls. The magnetic fields keep the plasma in perpetually looping paths because the electrical charges on the separated ions and electrons mean that they follow the magnetic field lines. As a consequence, the plasma does not touch the wall of the container.

There are several types of magnetic confinement system, but the approaches that have been developed to the point of being used in a reactor are tokamak and stellarator devices. Because of its versatility, tokamak is considered to be the most developed magnetic confinement system. Hence, it is the workhorse of fusion.

7.1.1 Tokamak

The tokamak, acronym for the Russian phrase *toroidál'naja kámara s magnitnymi katúškami* meaning toroidal chamber with magnetic coils, was designed in 1951 by Soviet physicists Andrei Sakharov and Igor Tamm [8]. It is a doughnut-shaped device in which the combination of two sets of magnetic coils, known as toroidal and poloidal field coils, creates a field in both vertical and horizontal directions. The magnetic fields hold and shape the charged particles of the plasma by forcing them to follow the magnetic field lines. They essentially create a “cage,” a magnetic bottle, inside which the plasma is confined. A strong electric current is induced in the plasma using a central solenoid, and this induced current also contributes to the poloidal field.

7.1.2 Stellarators

Unlike tokamaks, stellarators [9, 10] do not require a toroidal current to be induced in the plasma. Instead, the plasma is confined and heated by means of helical magnetic field lines. They are produced by a series of coils which may themselves be helical in shape. As a result, plasma stability is increased compared with tokamaks. Since heating the plasma can be more easily controlled and monitored with stellarators, they have an intrinsic potential for steady-state, continuous operation. The disadvantage is that, due to their more complex shape, stellarators are much more complicated than tokamaks to design and build.

7.2 Inertial confinement

After the invention of laser in 1960 at Hughes Research Laboratory in California, researchers sought to heat the fusion fuels with a laser so suddenly that the plasma would not have time to escape before it was burned in the fusion reaction. It would be trapped by its own inertia, hence the name “inertial confinement,” because it relies on the inertia of the implosion to bring nuclei close together. This approach to confinement was developed at Lawrence Livermore National Laboratory in California [11].

Within the context of inertial confinement, laser beams with an intensity of the order of $10^{14} - 10^{15} \text{ W/cm}^2$ are fired on a solid pellet filled with a low-density mixture of deuterium and tritium. The energy of the laser vaporizes the pellet

instantly producing a surrounding plasma environment for a short period of time. During the process, the density and temperature of the fuel attains a high enough value to ignite the fusion reaction.

The capability of present lasers does not allow the inertial confinement technique to obtain break-even conditions, simply because the efficiency for converting electrical energy into radiation is very low, about 1–10%. Consequently, alternative approaches are being explored to achieve the ignition temperature. One such approach involves using beams of charged particles instead of lasers.

8. Cold fusion

In 1989, researchers at University of Utah (USA) and University of Southampton (UK) claimed to have achieved fusion at room temperature in a simple tabletop experiment involving the electrolysis of heavy water (deuterium oxide) using palladium electrodes [12]. According to them, when electric current passed through the water, palladium catalyzed fusion by allowing deuterium atoms to get close enough for fusion to occur. Since other experimenters failed to replicate their claim, most of the scientific community no longer considers it a real phenomenon.

But in 2005, cold fusion got a major boost. Scientists at UCLA initiated fusion using a pyroelectric crystal [13]. They put the crystal into a small container filled with hydrogen, warmed the crystal to produce an electric field, and inserted a metal wire into the container to focus the charge. The focused electric field powerfully repelled the positively charged hydrogen nuclei, and in the rush away from the wire, the nuclei smashed into each other with enough force to fuse. The reaction took place at room temperature.

9. Fusion research

The aim of the controlled fusion research program is to achieve ignition, which occurs when enough fusion reactions take place for the process to become self-sustaining, with fresh fuel then being added to continue it. Once ignition is achieved, there is a net energy yield—about four times as much as with nuclear fission. As mentioned earlier, such conditions can occur when the temperature increases, causing the ions in the plasma to move faster and eventually reach speeds high enough to bring the ions close enough together. The nuclei can then fuse, causing a release of energy.

The plasma temperature needed for ignition is produced by external heating. Powerful methods were developed for this purpose. They are:

1. Heating by injection of neutral beams: In this method, neutralized particles with high kinetic energy, produced in an ion source, are injected into the plasma, whereby they transfer their energy to the plasma through collisions.
2. Heating by high-frequency radio or microwaves: When electromagnetic waves of appropriate frequency are beamed into the plasma, the plasma particles absorb energy from the field of the wave and transfer it to the other particles through collisions.
3. Heating with current: When an electric current is passed through the plasma, it generates heat in the plasma through its resistance. As the resistance decreases with increasing temperature, this method is only suitable for initial heating.

These methods produce temperatures of 100 million degrees Celsius in present-day fusion devices.

9.1 Research programs

Experiments with d-t fuel began in the early 1990s in the Tokamak Fusion Test Reactor in Princeton (USA) [14] and the Joint European Torus (JET) in Culham (UK) [15]. The world's first controlled release of fusion power using a 50–50 mix of tritium and deuterium with a fusion output of 16 MW from an input of 24 MW heating (Q-factor is 0.67) was achieved in 1991 by JET. The Q-factor is used to represent the ratio of the power produced in the fusion reaction to the power required to produce the fusion. It should not be confused with the Q-value of a reaction, which is the amount of energy released by that reaction. Obviously, Q-factor of 1 is breakeven. To achieve commercially viable fusion energy, the Q-factor must be much greater than one.

The 35-nation International Thermonuclear Experimental Reactor (ITER, “The Way” in Latin) project currently under construction in Cadarache, France, is the world's largest tokamak fusion reactor [16]. The goals of ITER are:

1. To operate at 500 MW (for at least 400 s continuously) with less than 50 MW of input power for a tenfold energy gain (Q-factor is 10).
2. Demonstrate the integrated operation of technologies for a fusion power plant and test technologies for heating, control, diagnostics, cryogenics, and remote maintenance.
3. Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating and stays confined within the plasma efficiently enough for the reaction to be sustained for a long duration.
4. Test tritium breeding because the world supply of tritium (used with deuterium to fuel the fusion reaction) is not sufficient to cover the needs of future power plants.
5. Demonstrate the safety characteristics of a fusion device, particularly the control of the plasma and fusion reactions with negligible consequences to the environment.

Launched in 2006, the project has been beset with technical delays, labyrinthine decision-making, and cost estimates that have soared. The reactor is now expected to be completed and become operational by 2030.

According to ITER Newsletter [16], “When completed, the plasma circulating in the core of the reactor will be 150 million degrees Celsius, or about 10 times hotter than the Sun. The massive superconducting magnets surrounding the core will be cooled to -270 degrees, as cold as the depths of space. So many of the technologies involved are really at the cutting edge.”

There is a considerable amount of research into many other fusion projects at various stages of development, but ITER is the largest, with 10 times more plasma capacity than any other reactor. Although China is a participating country in the ITER project, the Chinese are nevertheless building a tokamak reactor by themselves. Known as the Experimental Advanced Superconducting Tokamak (EAST), they managed to heat hydrogen gas to a temperature of about 50 million degrees Celsius [17].

Based on the information, technologies, and experience provided by ITER, physicists and engineers at the Culham Laboratory in Oxfordshire (UK) are working to develop a Demonstration Power Station (DEMO) which, if successful in terms of systems and performance, could be used as the commercial prototype, creating a fast track to fusion power. In collaboration with the Princeton Plasma Physics Laboratory, South Korea is also developing a tokamak fusion reactor named Korean Demonstration Fusion Power Plant (K-DEMO) [18]. Both EAST and K-DEMO are due for completion by year 2030.

Under an Italian-Russian agreement, Italy's National Agency for New Technologies, Energy and Sustainable Economic Development is developing a small tokamak reactor by the name of Ignitor [19]. The reactor is based on the Alcator machine at MIT [20] which pioneered the high magnetic field approach to plasma magnetic confinement. The scientists of the project believe that unlike the larger ITER reactor, Ignitor could be ready to begin operations within a few years.

By using magnetic fields that are twice as strong as those planned for ITER, two spin-off companies, one in the USA and the other in the UK, hope to create a sustainable fusion reaction in a machine as small as 1/70th the size of ITER. They also believe, according to the August 2018 issue of *Physics Today*, that their reactor will be able to produce more energy than they consume. It is expected to be operational before ITER, possibly by the mid-2020s.

The Germans are working on a non-tokamak fusion reactor called Wendelstein 7-X [21]. In a test run, they produced helium plasma that lasted for one-quarter of a second and achieved a temperature of 80 million degrees Celsius. The Germans believe that their stellarator design, similar in principal to the tokamaks, will provide an inherently more stable environment for plasma and a more promising route for nuclear fusion research in general.

Another stellarator, TJ-II, designed in collaboration with Oak Ridge National Laboratory (USA), is in operation in Madrid, Spain [22]. This flagship project of the National Fusion Laboratory of Spain is a flexible, medium-size stellarator—the second largest operational stellarator in Europe, after Wendelstein 7-X.

In 2014, scientists and engineers at the American aerospace conglomerate Lockheed Martin claimed to have made a major technological breakthrough in the development of a fusion reactor [23]. They are cautiously optimistic that an operational reactor with enough energy output to power a small city, yet small enough to fit on the back of a truck, can be built before the end of this decade. However, because of the absence of further details on how their reactor works, some scientists are skeptical about the claim.

According to MIT Technology Review [24], while ongoing research centered on large tokamaks may take decades before a commercially feasible fusion reactor is built, several privately funded companies and small university-based research groups pursuing novel fusion reactor designs have delivered promising results that could shorten the timeline for producing a prototype machine from decades to several years. On the other hand, scientists of the mega-projects believe that fusion power could become a reality more quickly if the present international funding for fusion research was increased.

There have also been significant developments in research into inertial confinement fusion (ICF). Research on ICF in the USA is going on at the National Ignition Facility [25] at the Lawrence Livermore National Laboratory in California and Sandia Laboratories in New Mexico. At Sandia, an entirely different method of ICF called the Z-pinch [26], which does not use laser at all, is being investigated. Instead, it uses a strong electrical current in a plasma to generate X-rays, which compresses a tiny d-t fuel cylinder. The other notable research activity on ICF is the Laser Megajoule project in Bordeaux, France [27]. All three projects are designed to

deliver, in a few billionths of a second, nearly 2 million Joules of energy to targets measuring a few millimeters in size. The main purpose of these projects is, however, to support research for nuclear weapons programs.

Thus far, none of the ICF facilities have achieved scientific breakeven, which is a gain of unity. However, for making fusion energy viable in commercial power plants, the gain has to be much greater than breakeven. Since lasers are very inefficient machines, gains of at least 100 are needed for a plant to produce net power output. To that end, researchers at Lawrence Livermore National Laboratory are exploring other approaches to developing ICF as a source for energy.

10. Advantages/disadvantages of fusion reactors

There are many advantages of fusion reactors:

1. They will produce at least five times more energy than the amount of energy it will need to heat the fusing nuclei to the desired temperature. Furthermore, it is estimated that to run a 1000 MW power plant for a year, a fusion reactor will require about 3000 m³ of water (source of deuterium) and 10 tonnes of lithium ore, while the current fission reactors consume 25–30 tonnes of enriched uranium. Clearly, gram for gram, fusion reactor wins the energy race by a wide margin.
2. Fusion fuels are widely available and nearly inexhaustible. Deuterium can be distilled from all forms of water, while reserves of lithium, both terrestrial and sea-based, which would be used to produce tritium, would fulfill needs of fusion reactors for millions of years.
3. Unlike fission, fusion will have a low burden of radioactive waste. They will not produce high-level nuclear wastes like their fission counterparts, so disposal will be less of a problem. Fusions by-product is helium—an inert, nontoxic, and nonradioactive gas used to inflate childrens' balloons. Besides, there will be no fissile material that could be diverted by terrorists to build “dirty bombs.” Moreover, a fusion power station would not require the transport of hazardous radioactive materials.
4. Fusion reactors are inherently incapable of a runaway reaction that could result in a core meltdown, the most serious calamity possible in a fission reactor. This is because there is no critical mass required for fusion. Besides, fusion reactors work like a gas burner; once the fuel supply is shut off, the reaction stops. There will, therefore, be no off-site radiation-related deaths, even from a severe accident.
5. Despite being technically nonrenewable, fusion has many of the benefits of renewable energy sources, such as being a long-term source of energy emitting no greenhouse gases. Besides, because it is not dependent on weather, fusion could provide uninterrupted power delivery, unlike solar and wind power.

Although fusion does not generate long-lived radioactive products and the unburned gases can be treated on site, there are nevertheless few concerns related to the radioactivity induced by the high-energy neutrons (~14 MeV) that are produced during the d-t reaction. They are:

1. Some radioactive wastes will be produced due to neutron activation of lithium to produce tritium inside the reactor, but their inventory will be much less than those from fission, and they will be short-lived. Nonetheless, if accidentally released in the air or water, tritium will remain radioactive for a period equal to at least 10 half-lives or 120 years.
2. The neutrons will irradiate the surrounding structures giving rise to radioactive nuclides, which ultimately have to be disposed of in some waste facility. But their stock will be considerably lower than that from actinides used in fission-based reactors.
3. Since most of the energy in the d-t reaction is carried away by the neutrons, this could lead to neutron leakage that could be significantly higher than uranium reactors. More neutron leakage means more shielding and improved protection for workers at the power plant.

11. Fusion torch

A fascinating application for the abundant energy that fusion may provide is the fusion torch, a star-hot flame or high-temperature plasma into which all waste materials—whether liquid sewage or solid industrial refuse—could be dumped [28]. In the high-temperature environment, the materials would be reduced to their constituent atoms and separated by a mass-spectrograph-type device into various bins ranging from hydrogen to uranium. Thus, a single fusion plant could, in principle, not only dispose of thousands of tons of solid wastes per day but also convert them into a few reusable and saleable elements, thereby closing the cycle from use to reuse.

12. Conclusion

Projection for the demand of energy depends on the growth of population, because the more people there is, the more energy will be used. The current world population of 7 billion is expected to reach 11 billion in 2100. This means if we want to maintain a better or at least the same standard of living, global consumption of energy could double, or perhaps triple, by the end of this century.

With the incorporation of improved safety features and new generation of reactors, nuclear fission will probably continue to make a major contribution to electricity generation. However, its growth could be curtailed by issues of public and political acceptability. Supplies from some renewable sources of energy, such as solar or wind, are not guaranteed either, because they are reliant on weather conditions. Technological challenges for other sources, ocean thermal energy and hydrokinetic energy from rivers, for example, have not yet been fully developed. So, for future energy security, the answer is nuclear fusion.

Advocates acknowledge that fusion technology is likely many decades away. The reason, these systems are intrinsically large, so large that we cannot test the physics and technology of fusion on a lab bench and then mass-produce fusion reactors. Consequently, these large, first-of-a-kind facilities take time to construct.

Despite the enormity of the projects, we have succeeded in creating a short-lived artificial Sun on Earth via experimental fusion reactors. Once commercial fusion reactors become a reality, there will be a paradigm-shifting development in the global energy mix. In particular, our dependence on the rapidly depleting supply of

fossil fuels and uranium will be drastically reduced. More importantly, fusion power can easily secure our planet's future, given the abundance of fuels and near-limitless energy produced from fusion reactions. Additionally, with no risk for proliferation and minimum radioactive waste generated, nuclear fusion would offer a clean, relatively safe, zero greenhouse gas-emitting, and long-term source of energy, with the potential to produce at least 20–25% of the world's electricity by 2100.


To conclude, nuclear fusion energy may not have the magic wand that would solve our energy problem. Nevertheless, it has the potential to be an attractive energy source that can be deployed as major pressures rise on existing energy supply options. Also, it would go a long way in slowing down, if not mitigating, the unrelenting climb of the temperature of our planet.

Author details

Quamrul Haider
Department of Physics and Engineering Physics, Fordham University, Bronx,
New York, USA

*Address all correspondence to: haider@fordham.edu

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