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Nuclear Fusion Power Plants

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Abstract

Nuclear fusion, the process that powers the sun and the stars, is heralded as the ultimate energy source for the future of mankind. The promise of nuclear fusion to provide clean and safe energy, while having abundant fuel resources continues to drive global research and development. However, the goal of reaching so-called “breakeven” energy conditions, whereby the energy produced from a fusion reaction is greater than the energy put in, is yet to be demonstrated. It is the role of ITER, an international collaborative experimental reactor, to achieve breakeven conditions and to demonstrate technologies that will allow fusion to be realized as a viable energy source. However, with significant delays and cost overruns to ITER, there has been increased interest in the development of other fusion reactor concepts, particularly by private-sector start-ups, all of which are exploring the possibility of an accelerated route to fusion. This chapter gives a comprehensive overview of nuclear fusion science, and provides an account of current approaches and their progress towards the realization of future fusion energy power plants. The range of technical issues, associated technology development challenges and future commercial opportunities are explored, with a focus on magnetic confinement approaches.

Keywords: nuclear fusion, power plant, plant design, plant operation, environmental impact, sustainability, DEMO

1. Introduction: a brief history of nuclear fusion

Under enormous pressures and temperatures, two or more atomic nuclei are able to overcome the coulombic barrier and, through the quantum tunneling effect, join together to create a heavier nucleus, and to release enormous amounts of energy in the process. This reaction is called *nuclear fusion*. It is the process that combines lighter elements to create heavier elements, from which the energy released is what powers the sun and the stars [1]. Nuclear fusion has

the potential to provide almost limitless energy for mankind, as its primary fuel sources are abundant [2], there is no risk of a runaway reaction or meltdown, and no long-lived high-level radioactive waste or harmful greenhouse emissions are produced (see Section 5) [3]. As such, the possibility of creating a star on earth and harnessing the energy from the fusion reaction is heralded as the solution to all of mankind's energy problems [4]. The aim of this study is to provide an overview of current development efforts into nuclear fusion as an energy source.

Figure 1 illustrates the binding energy of atomic nuclei and shows the differences between the easily confused nuclear *fusion* and nuclear *fission* reactions. Nuclear fission involves the splitting of unstable heavy atomic nuclei (illustrated by the leftward arrow on the right-hand side of the figure), whereas fusion involves the fusing of light atomic nuclei (illustrated by the upward arrow on the left-hand side of the figure).

Nuclear fusion was first observed earlier than nuclear fission. In 1934, an experiment involving scientists Oliphant, Harteck and Lord Rutherford, where by bombarding deuterium ions into target compounds containing deuterium, they observed that a new isotope of hydrogen and a neutron had been produced [6]. They theorized that a “hydrogen transmutation effect” had taken place [6], and it was later proven that this effect had in fact been the D-D fusion reaction (the reaction between two deuterium isotopes).

Although discovered prior to World War II, efforts to utilize the fusion reaction as a source of energy did not materialize until the 1950s [7]. Meanwhile, scientific understanding of the nuclear fission reaction, and the mechanisms by which energy could be produced from it, lead to rapid commercialization of fission technology in the early 1960s. During the same period, nuclear fusion research was considered slow, and was considered as being in “Purgatory” [8] due to the relative lack of progress as compared with fission. However, unlike fission, which occurs spontaneously in certain elements in nature and for which the reaction can be easily controlled in manmade reactors, fusion only occurs in stars (and the supernovae of stars) where the intense gravitational pressure and high temperatures allow the fusion reaction to take place. Given

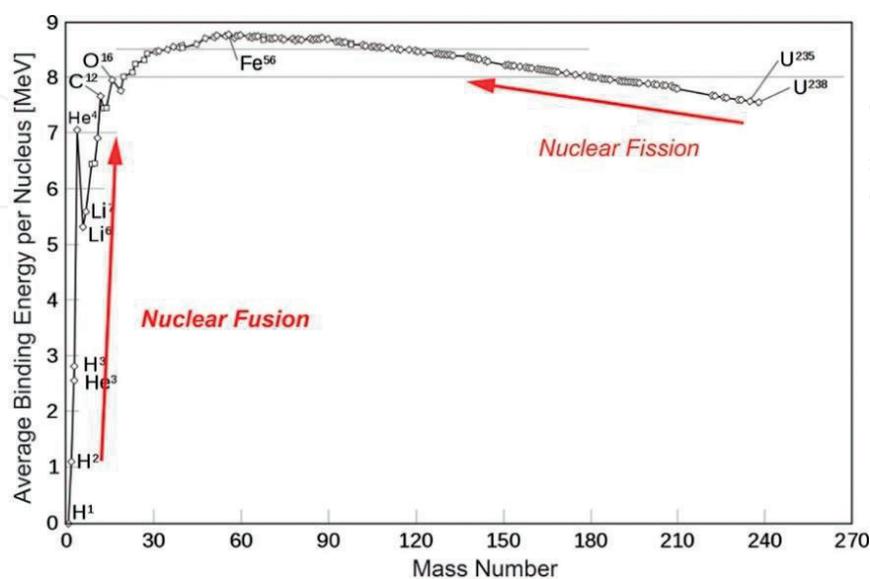


Figure 1. Binding energies of atomic nuclei (from hydrogen to uranium) [5].

the extremity of the conditions required, it was immediately clear that the task of mimicking a star and harnessing energy from the fusion reaction on Earth would be a significant challenge.

In 1965, promising experimental results were published by the Soviet Union from a novel nuclear fusion device called a *Tokamak*. A tokamak, which is a Russian acronym for “*Toroidalnaya Kamera Magnitnaya saksial’nyy*” (which translates to “toroidal chamber with axial magnetic field”), is a donut-shaped device that was designed for the purpose of confining a high temperature plasma using a magnetic field, which is explained in more detail in Section 3. At first, experimental findings from tokamak experiments were largely ignored by the international fusion research community. However, by the beginning of 1970s the efficacy of the tokamak became apparent, and many countries followed by developing their own tokamak machines. Notable tokamaks around the world include: the Joint European Torus (JET) in U.K. (designed, constructed, and operated by the European Union, and Euratom, starting in the late 1970s and continues operation today), the Japan Torus-60 (JT-60) in Japan (which is now being upgraded to JT-60SA “Super Advanced”).

Since the end of the Cold War, focus has shifted towards international collaboration on the development of fusion. Together, the European Union, India, Japan, Russia, United States, South Korea and China are involved in the construction of the ITER tokamak (previously an acronym for International Thermonuclear Experimental Reactor, but now solely referred to as ITER, which is Latin for “*the way*”). A diagram showing the cross-section of ITER is shown in **Figure 2**. Under construction in Saint-Paul-lès-Durance, near Provence, in France, ITER will be the largest fusion reactor in the world to date and is considered the next major step in the path towards fusion energy. The primary objective is for ITER to yield a fusion reaction that produces five times more energy than is needed to sustain the fusion reaction (see Section 2), but it will also demonstrate the scientific and technological feasibility of fusion energy using tokamaks. “First plasma” in ITER (the start of preliminary D-D operation) is currently scheduled to begin in 2025, but the start of full power D-T operation (the reaction between deuterium and tritium), which will allow an attempt at achieving breakeven conditions, has been pushed back almost two decades from the original start date and will now begin in 2035.

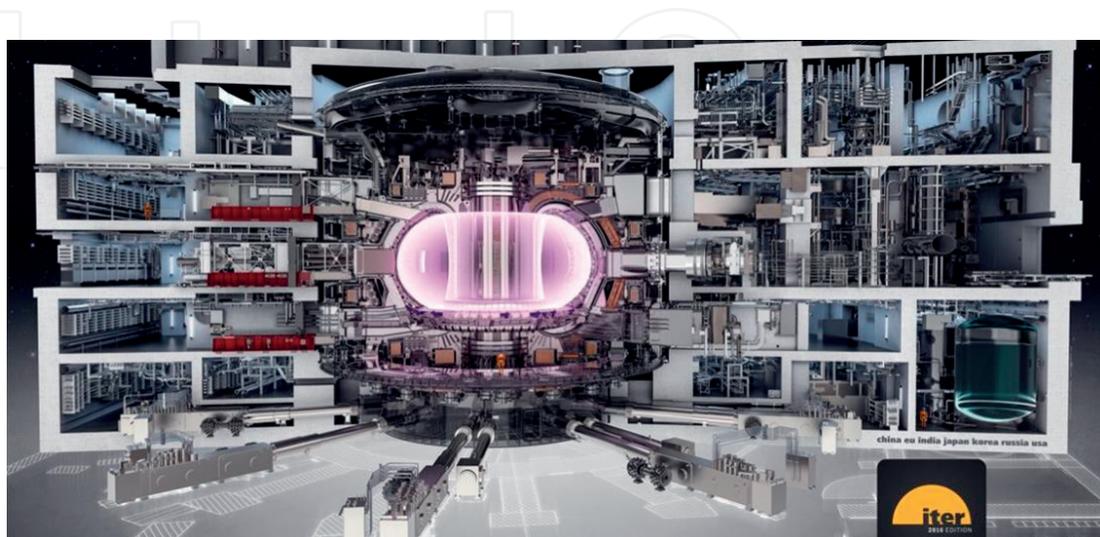


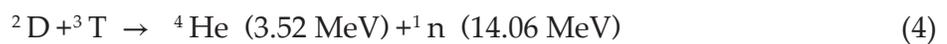
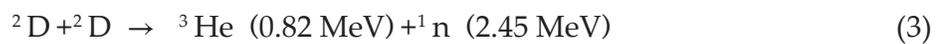
Figure 2. ITER tokamak and plant systems [9].

2. Fundamentals of nuclear fusion science

During the fusion of two or more light atomic nuclei, the mass of the product of the fusion reaction is slightly less than the sum of the reactants. This difference in mass is the conversion of mass into energy, as was theorized by Albert Einstein, and later proven. The relationship between mass and energy is shown in Eq. (1), where E , m and c are the energy released, the mass difference, and the speed of light respectively. In case of a nuclear fusion reaction, the surplus binding energy will be released as kinetic energy of particles, as detailed below.

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

As shown in **Figure 1**, a helium-4 (${}^4\text{He}$) nucleus has the greatest binding energy of any atom lighter than carbon-12 (${}^{12}\text{C}$), and as such it is therefore the most stable of the light elements. Therefore, in terms of effectively utilizing energy from the nuclear fusion reaction, and to produce a stable product, it is most desirable to fuse light atoms that result in the production of a helium nucleus. Fusing lighter atomic nuclei has another significant advantage. The lower electric charge of lighter atoms leads to a reduced level of repulsion when interacting with other atomic nuclei, increasing the likelihood that a fusion reaction will occur. Nuclear fusion reactions between the lightest isotopes of hydrogen, deuterium (${}^2\text{D}$) and tritium (${}^3\text{T}$), as shown as Eqs. (2)–(4), are therefore the best candidates for the fuel cycle in future fusion reactors [3].



But of the three reactions shown, which offers the best option to be utilized as an energy source? The difficulty of a nuclear fusion reaction can be expressed by the reactivity, which is defined as the probability of a reaction occurring, per unit time, per unit density of target nuclei [10]. Reactivities of nuclear fusion reactions can be obtained by a multiplication of the nuclear cross section σ , and the relative velocity v [10]. **Figure 3** shows the averaged reactivity $\langle\sigma v\rangle$ of the reactions Eqs. (2)–(4), as well as other possible fusion reactions between light atomic nuclei. As is clear, the lower the reactivity, the more extreme the conditions must be for the fusion reaction to occur. The figure shows that the reactivity between atomic nuclei of deuterium and tritium (the D-T reaction) is the most favorable, and it is for this reason that efforts are currently focused on producing a D-T fusion reactor. However, despite the fact that the reactivity of the D-T reaction makes it favorable from a physics perspectives, as detailed in Section 6, due to complications surrounding the long-term availability of tritium, unwanted chemical properties, and the higher energy neutrons produced by the reaction, other fusion fuels that avoid the use of tritium may be preferable. Of these, the D-D fusion reaction, as shown in Eqs. (2) and (3), as well as other aneutronic fusion reactions (reactions not resulting in the production of neutrons), are considered to be the best long-term options for future fusion reactors.

Although the D-T fusion reaction requires the lowest kinetic temperature for the fusion reaction to occur, extremely high temperatures in the order of tens of keV are still required. Fusion reactors must be designed to provide and contain the conditions needed for nuclear fusion reactions to occur. In a fusion reactor, atoms of deuterium and tritium are heated to very high temperatures. At high temperatures, the electrons surrounding an atom separate from the nucleus, forming an ionized and electrically conductive substance called a *plasma* (plasma is the fourth state of matter). For fusion to occur, the plasma containing the fusion fuels must reach the thermal (kinetic) energy required, which requires the need to both contain and to heat the plasma. Plasma can be contained by magnetic fields, as it is positively charged. Being electrically conductive, it is also possible to induce a current in the plasma. There are a number of ways fusion plasmas can be controlled, and these are explained in Section 3.

To generate net positive energy from a fusion reaction, the energy released by the reaction must be greater than the energy that is required to induce the reaction. In the case of a fusion reactor,

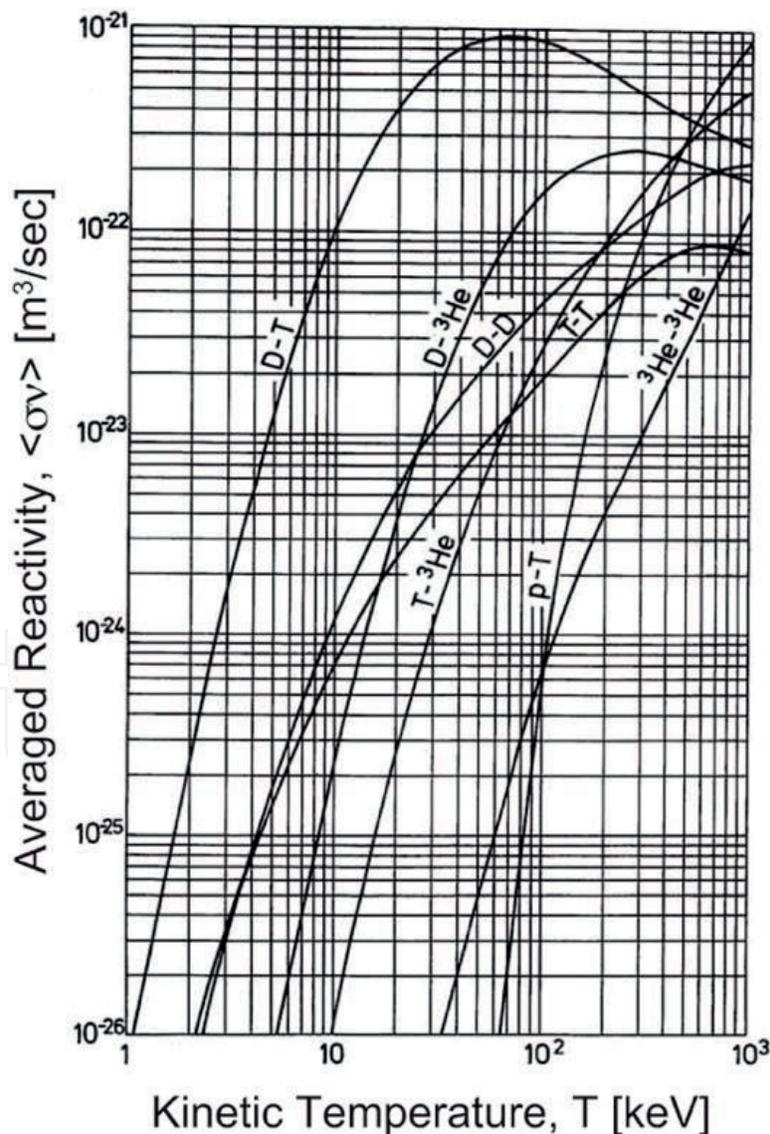


Figure 3. Averaged reactivity $\langle\sigma v\rangle$ of nuclear fusion reactions between light atomic nuclei [11, 12].

this is the ratio of the energy output from nuclear fusion reactions in the plasma to the energy supplied to sustain the plasma, and is known as the *fusion energy gain* Q , or Q_{fus} . The conditions to achieve $Q = 1$, the moment at which the energy produced is equal to the energy put in, is known as *scientific breakeven conditions*. In the case of a fusion reactor, auxiliary system power requirements and inefficiencies in the production of electricity mean that scientific breakeven conditions are not sufficient for a commercial fusion reactor. Instead, the ratio of energy production from the fusion reactor must be compared against the total energy consumption of the whole fusion power plant. This is known as the *engineering gain* Q_{eng} . Similarly, the conditions required to achieve $Q_{eng} = 1$ is known as “engineering breakeven,” and it is achieving these conditions that is the true goal on the pathway to the realization of fusion energy.

There are three ways to improve the value of Q , in order to get closer to fusion conditions. Firstly, by increasing the rate of the fusion reaction (increasing the output energy) whilst simultaneously reducing the level of external heating needed (decreasing in the input energy), the value of Q can be increased. This is shown by the volumetric *rate of the fusion reaction*, f , as in Eq. (5), where n is the density of the fuel, and $\langle\sigma v\rangle$ is the averaged reactivity. Since $\langle\sigma v\rangle$ is proportional to the square of T , the volumetric rate of fusion reaction f is proportional to n^2T^2 , thus when both are increased it leads to an increase in Q . The rate of the fusion reaction is dependent on both the density of the plasma, and on the plasma temperature, and increasing the temperature and density are thus two of the ways to increase Q .

$$f = 0.25 n^2 \langle \sigma v \rangle \quad (5)$$

The third way to increase Q pertains to the efficiency of a fusion plasma to maintain its high-temperature and high-density plasma conditions. This is known as the *energy confinement time* τ_E and is expressed by Eq. (6), where W and P_{heat} are the thermal energy and the heating energy of the plasma, respectively [13]. The confinement time τ_E is the first-order delay time constant of the plasma thermal energy when the heating energy $P_{heat} = 0$, and is a measure of how well a fusion plasma can be contained.

$$\frac{dW}{dT} = P_{heat} - \frac{W}{\tau_E} \quad (6)$$

In summary, Q_{fus} is closely linked to the plasma density, the plasma temperature, and the efficiency of contained thermal energy (confinement time). All must be increased to achieve the conditions required for nuclear fusion. These three factors combine as $nT\tau_E$, which is known as *the fusion triple product*, or the *Lawson criterion* [14]. The triple product is used to evaluate the performance of a fusion reactor, and efforts have seen the value of the triple product increase steadily over time, although little improvement has been made in the past two decades.

3. Nuclear fusion reactors

3.1. Approaches to fusion reactors

Although several approaches to controlling and containing a fusion plasma exist, the two primary approaches being explored are based on the concept of *magnetic confinement*, and *inertial confinement*.

Magnetic confinement fusion (MCF) reactors are the more advanced of the two approaches, and they utilize magnetic fields generated by electromagnetic coils to confine a fusion plasma in a donut-shaped (torus) vessel. There are two primary types of torus-shaped fusion devices. The *tokamak*, such as ITER (as introduced in Section 1), utilizes magnetic coils arranged around a torus-shaped vessel, which generates a toroidal magnetic field to confine the plasma, and uses a secondary poloidal magnetic field to drive the current in the plasma [13]. Other tokamak variants, such as the spherical tokamak design, which has a lower aspect ratio (the ratio of the outer radius to the inner radius of the torus), exhibits different and potentially better plasma performance but with the tradeoff of increased difficulty in engineering design [22].

Another magnetic confinement concept is the *stellarator*, which uses magnetic coils in a helical configuration around the plasma vessel, creating a spiral-shaped magnetic field which is used to drive the current. The differences between tokamak and stellarator systems are illustrated in **Figure 4**. The stellarator is considered to be a potential long-term solution, and stellarator-based fusion reactors are actively being explored, but like the spherical tokamak may present a great challenge in engineering design [15].

Unlike magnetic confinement approaches, *inertial confinement fusion* (ICF) approaches attempt to externally heat and compress fusion fuel targets to achieve the very high temperatures even higher densities required to initiate the nuclear fusion. For most ICF concepts and approaches, high power lasers are used to compress and heat the fuel.

Recently, a third approach, which exploits the parameter space between the conditions produced and needed for magnetic and inertial confinement, has gained traction in recent years, and is receiving much scientific, and even commercial, attention. *Magnetized target fusion* (MTF), sometimes known as *magnetized inertial fusion* (MIF), looks to exploit the use of higher density plasmas than for MCF approaches, but lower power lasers and other drivers than those used in ICF approaches. MTF may offer a unique route to fusion, and the accelerated development of a number of unique concepts has seen significant support, particularly in the United States of America where the U.S. ARPA-E (Advanced Research Projects Agency-Energy) “ALPHA” program has provided support for exploration into the magnetized target fusion route to fusion [17].

3.2. Progress in reactor development

As described in Section 2, nuclear fusion reactors are often evaluated by their ability to achieve high plasma density n , confinement time τ_E , and temperature T . As such, the history of fusion reactors is best viewed as a history of the improvement of the fusion gain Q on the *Lawson*

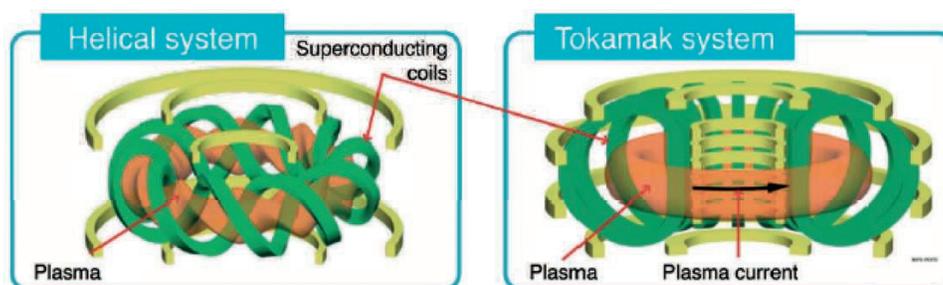


Figure 4. Helical and tokamak magnetic confinement fusion reactors [16].

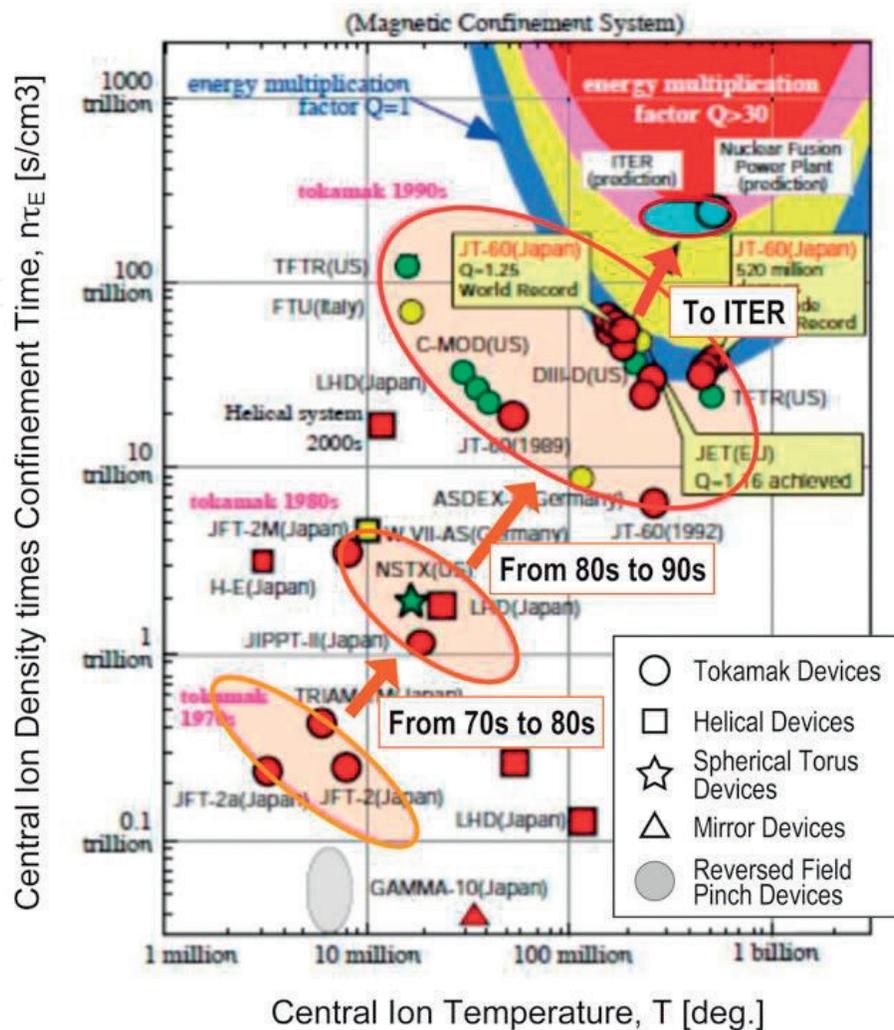


Figure 5. The development of fusion reactors since the 1970s (adapted from [18]).

Diagram. The Lawson Diagram in Figure 5 illustrates the progress in fusion reactor development, showing progression towards the Lawson criterion, with the central ion temperature (T) shown on the horizontal axis, and the product of plasma density the energy confinement time ($n\tau_E$) shown on the vertical axis. The diagram shows that since the 1970s fusion reactors have seen a steady improvement towards scientific breakeven conditions ($Q = 1$). However, whilst the scientific community wait on the delayed ITER project to begin operation, progress towards breakeven has stagnated over the past two decades, as all focus has been on ensuring ITER's success, which has diverted effort, resources in the way of both funding and manpower, and time for the exploration of other pathways, and even alternative tokamak concepts.

4. Nuclear fusion power plant design and operation

4.1. Harnessing the energy from the fusion reaction

All information presented here pertains only to the D-T fusion reaction, as the majority of development efforts are based on the D-T fuel cycle. However, it is worth mentioning that aneutronic

fusion fuels, such as the proton-boron-11 reaction, or those involving helium-3, are considered to present promising and viable alternatives for long-term use as fuels for fusion energy. Refer to [19] for a comprehensive overview of the range of potential fuel cycles for future fusion reactors.

The primary energy released by the D-T fusion reaction is in the form of kinetic energy, which is carried by the products of the reaction. Of the two products, the majority of the energy is carried by the neutron (14.1 MeV), with the remainder being carried by the helium nucleus (3.5 MeV). As helium carries a positive charge, it will be affected by magnetic fields of the reactor, and as such the majority of the kinetic energy carried by the helium nuclei from fusion reactions will remain in the plasma, with the energy transferred to the plasma provide a self-heating effect to help sustain the fusion reaction. However, the kinetic energy carried by the neutrons, which are uncharged particles, will not remain in the plasma and instead will deposit their energy as heat in the walls of the reactor. Fusion power plant concepts intended for energy production will capture the energy carried by the neutrons in a blanket surrounding the reactor. The heat energy captured by the blanket will be extracted and converted into electricity through a thermodynamic cycle. It should be noted that whilst the energy is transferred by the neutrons, they also have potential to cause significant radiation damage. This is a major issue for future fusion reactors and must be designed for (see Section 5.1).

4.2. Energy production

The *Rankine cycle* is a closed steam turbine system used to generate electricity by converting energy from a heat source. A standard Rankine cycle follows a four-stage process. Water enters a *boiler*, for which the energy is provided by a heat source (in this case a fusion blanket which is heated primarily by the energy deposited from neutrons), where the energy from the heat carried away in the water is hot enough to form a saturated steam. The saturated steam passes through a *steam turbine*, where it expands transferring its energy to a turbine as rotational energy, which is used to turn a generator to produce electricity. Following the expansion through the turbine, the resulting wet steam enters the *condenser*, where it is converted back into the liquid phase. Finally, the liquid water passes through a *pump*, which returns the working fluid from a low-pressure boiler to a high-pressure boiler, and the cycle repeats. Currently, the Rankine cycle, as well as variations of the Rankine Cycle such as the reheat and regenerative Rankine cycle, are widely used at coal, oil and nuclear fission power plants. Due to the similarities in the conditions of nuclear fission reactors in that they produce high-grade heat, fusion power plants of the future are also expected to employ a Rankine cycle.

The *Brayton cycle* is now utilized at many natural gas power plants. As nuclear fusion reactors have the potential to operate at high-temperatures, fusion power plants of the future operating on the Brayton cycle also have the potential to achieve a higher energy production efficiency than systems using a Rankine cycle. Proposals to use fusion in more advanced electricity generation cycles include the possibility of using the *Integrated Gasification Fuel Cell (IGFC) cycle* or the *Magnetohydrodynamic (MHD) generator cycle*. In fact, the potential for fusion to produce high-grade process heat opens a number of avenues for future energy generation technology. Novel ideas for process heat applications of nuclear fusion, for purposes such as hydrogen production [20], high-temperature salt water desalination [21], or biomass gasification could facilitate the deep decarbonization of a larger proportion of primary energy markets, allowing fusion technology to be used to better support ever-increasing global energy demand.

4.3. Operation modes

There are two proposed modes of plant operation for electricity production in fusion power plants. The first is *steady-state mode*, which would allow the plant to generate electricity at a constant rate, as is the case in current nuclear fission power plants. Alternatively, fusion power plants could operate in *pulsed mode*, whereby the reactor system alternates between a short plasma burning period (concept designs see burn period range from 30 min to several hours), and a shut-off period (also known as a *dwell period*) to recharge for the next pulse. Some plant concepts based on a pulsed operational mode are designed with thermal reservoirs that use residual heat to enable continued electricity generation during dwell periods. Concepts that cannot manage continuous energy production in pulsed mode are considered intermittent and thus may not be viable as an electricity generating source but may still be useful for process heat applications, as detailed in Section 4.2.

An alternative is to design smaller (“compact”) fusion reactors modules, which then operate together in a modular power plant configuration. By designing a power plant so that of a set of fusion reactor modules, some are operational whilst others are in a dwell period, intermittent fusion devices could still prove viable for electricity production. A modular power plant configuration also opens up the possibility of load-following capability and co-generation, by switching on a greater number of modules to provide electricity at times of high grid demand and then switching the output for the purposes of process heat applications at times of low grid demand. This concept is possible with some of the approaches being explored by various fusion initiatives, and is suggested in [22] (see Section 6), as well as by an array of concepts employing the use of fission SMRs (Small Modular Reactors), which share many similarities with the modular fusion power plant concept [21, 23].

5. Challenges to the realization of a nuclear fusion power plant

5.1. Science, engineering and technology

The science, engineering and technology challenges ahead on the route to commercial fusion are vast and wide-ranging. Principally, for magnetic confinement D-T reactor concepts, the primary technical issues that must be overcome are: [15].

- Stable operation of fusion plasmas
- Design and development of a heat exhaust system (known as the divertor)
- Development of neutron-resistant fusion materials
- Development of tritium breeding technology
- Development of reliable magnet systems

For the success of any fusion device, the operation and control of a high-performance plasma is crucial. The development of reliable plasma regimes with mitigation procedures that prevent

instabilities and disruptions in the plasma from causing damage to the walls of the reactor are the subject of much current research around the globe and is a primary focus on the ITER project [15]. Further, to handle the heat from the plasma, and to remove the helium “ash” (the alpha particles) that is produced by the D-T fusion reaction itself, a plasma heat exhaust, known as a divertor, is also required. An integrated divertor design must be developed to be effective at handling the intense heat (10 MW/m^2 is the design basis for ITER [15]) and the high neutron loads over the long operational timescales that will be required for a fusion power plant [15, 24]. Divertors are specific to the tokamak approach, but any MCF power plant concept, or perhaps even MTF approaches, will have to consider a power handling and plasma exhaust system.

In addition to materials needed for the divertor, plasma facing materials (sometimes known as the first wall) must also be developed to provide radiation shielding for protection of the magnets, diagnostics and control equipment, as well as workers and the environment (using a bio-shield), whilst simultaneously allowing neutrons through to the tritium fuel breeding blanket where the energy deposited is used to produce electricity and to breed new fuel to sustain the fusion fuel cycle (see below). The requirements of fusion materials differ to those used for nuclear fission reactors. The neutrons from the D-T fusion reaction are of a much higher energy, and with the reduction of nuclear waste and safety in mind, materials for fusion are subject to judicious selection to ensure that long-lived radioactive waste is not produced through the interaction of fusion neutrons with the surrounding reactor structure [21]. In eliminating certain isotopes, the list of materials available for use in fusion reactors becomes significantly limited, thus providing an added challenge on top of an already difficult problem. An example of the trade-offs is apparent when considering the development of Reduced Activation Ferritic Martensitic (RAFM) steels for fusion applications, which upon neutron irradiation better retain their properties and do not produce any long-lived radioactive waste, but instead suffer from other performance limitations and have more of a limited thermal operation range [25].

Neutron resistant materials also play a critical role in the structure of the tritium breeding blanket systems. The tritium breeding systems have two primary purposes: to breed new tritium fuel from D-T fusion neutron interaction with lithium, and to capture and extract the energy carried by the neutrons in the form of heat so that energy can be produced (see Section 4). Challenges in the design of breeding blankets are wide-ranging. Materials selection, the removal of heat and associated thermal hydraulic challenges, as well as the breeding mechanism itself, all present disparate problems but require an integrated solution. To date, no proof-of-concept for tritium breeding technology has been demonstrated, though a range of designs exist, and preliminary testing and computer modeling has been the focus in the absence of experimental data. However, even if breeding technology is developed, issues surrounding the sustainability of breeding blankets may present an additional hurdle, as discussed in Section 5.5 [15, 26].

The final of the core challenges for fusion is in the development of efficient superconducting magnets, which are required to provide the magnetic field to contain a fusion plasma. Until recently, most effort was focused on the use of low temperature superconducting (LTS) magnets, which are capable of carrying the high fields and currents necessary for large scale magnetic confinement fusion reactors, but that are large in size, and must be cooled to liquid helium temperatures ($\sim 4 \text{ K}$) at significant cryogenic cost. Recent developments in magnet technology has seen the development of high-temperature superconductors (HTS) which can carry greater currents at

higher field than LTS, and with greater cryogenic efficiency, owing to the operating temperature (“high-temperature” is a misnomer that refers to potential high-performance magnet operation at 20–30 K, rather than 4 K). Development in HTS, which may lead to the development of more efficient smaller fusion reactors as they are capable of operating at higher field [22, 27].

All issues have interdependencies, and an integrated solution is required and being sought for future fusion devices, and in the development approach. See [15, 28, 29].

5.2. Safety

Unlike nuclear fission reactors, nuclear fusion reactors do not have any risk of a runaway reaction or meltdown. In the case of any abnormalities in fusion reactor conditions, such as an abnormal plasma pressure or density spike, the plasma will dissociate and collapse, and the fusion reaction will cease. The level of decay heat in a fusion reactor after the termination of the plasma is very low compared with fission reactors, which must be cooled after shutdown to prevent core melt. In principle, nuclear fusion power plants do not require an Emergency Core Cooling System (ECCS), as even in a Loss of Cooling Accident (LOCA) the plasma inside the reactor would dissociate due to the influx of impurities from the reactor vessel walls as the surfaces heat up due to the lack of coolant available. In such an event, once the plasma has dissociated, all that remains is residual decay heat, for which studies suggest that the small temperature increases do not lead to melting, and therefore decay heat in a fusion power plant is considered as a low safety risk [30]. Despite this, consideration of such accident scenarios will still be made based on the rigorous method of Probabilistic Risk Assessment (PRA) [30].

Nuclear fusion power plants will not produce high level or transuranic radioactive waste like that produced by fission power plants. However, nuclear fusion power plants will still produce large quantities of intermediate level waste as a result of the existence of high energy neutrons and the in-vessel tritium-contaminated (tritiated) dust that becomes embedded in the reactor walls and components. Radioactive waste from fusion is unavoidable, even with efforts to develop materials such as RAFM steels to reduce the radioactivity and quantities of waste from the reactor structure. Another important example of the impossibility of avoiding the production of radioactive waste from fusion is in the selection of breeding blanket materials, as the neutron irradiation of lead, a crucial breeding material (neutron multiplier) can result in the production of the isotope polonium-210, which is a strong alpha emitter. As such, both issues present a challenge, as the waste from fusion power plants will remain significantly radioactive for a number of decades, perhaps even presenting a higher level of radiological risk than the waste produced in fission reactors in the short-term, and tritiated materials will require novel handling techniques [31]. While the risks associated with radioactive materials in the long-term are considered to be lower than those associated with waste produced from fission reactors, which can last for millions of years, it is likely that a similar level of regulation and licensing will be required to ensure that plant design and waste handling is fit for purpose, safe, and factored in to design and costing.

5.3. Nuclear proliferation and security risks

Nuclear fusion power plant concepts are generally considered to have a lower risk of nuclear proliferation. Nuclear fusion power plants will not handle any currently designated

special nuclear materials. Currently safeguarded are: ^{239}Pu , ^{233}U and enriched uranium (^{235}U). However, it is not inconceivable that weapons-grade ^{239}Pu or ^{233}U could be produced using the neutrons from a fusion reactor by replacing the blanket materials with natural uranium or thorium [32]. Moreover, tritium, the primary fuel for fusion, can be used to boost the yield of thermonuclear fission and fusion weapons, and thus careful accountancy of the fuel will be required [33]. While the nuclear proliferation and security risks regarding nuclear fusion power plants are significantly lower than those required for fission power plants, it is likely that stringent safeguarding for fusion power plants will be required. These must be developed in accordance with International Atomic Energy Agency (IAEA) recommendations.

5.4. Environmental impacts

Although fusion power plants will release small quantities of tritium to within already defined limits, they will not produce greenhouse gases or other air pollutants [34]. As a result, the environmental impacts associated with nuclear fusion power plants will instead be primarily attributed to construction, operation and maintenance, including fuel supply chains, and waste disposal. Environmental Life Cycle Assessments (LCA) suggest that life cycle greenhouse gas emissions of nuclear fusion electricity generation will be somewhere between 6 and 12 g CO₂ equivalent per kWh of electricity production. This is in line with recent renewables estimates [35], and current light water nuclear power plants (5.7 g/kWh), and an order of magnitude lower than for coal power plants (270 g/kWh) [36–38].

5.5. Sustainability

The fuels of nuclear fusion power plants are deuterium and tritium. Deuterium is an isotope of hydrogen with the isotopic ratio of 150 ppm, or 1 part in 6700 atoms of hydrogen. As such, deuterium is abundant in seawater and can be extracted using well-established separation processes. Tritium, on the other hand, does not occur in nature in any significant quantity, and is only produced by commercial purposes as a by-product in heavy water CANDU fission reactors. Tritium is a radioactive isotope, decaying with a half-life of 12.3 years, and with supply coming only from CANDU reactors, supply is severely limited, as a global stockpile of only around 30 kg is available for commercial use worldwide (and the same stockpile must supply ITER with almost 20 kg). That commercial fusion reactors require 55.6 kg of tritium per year per GW (thermal) for operation, future fusion power plants cannot depend on an external supply of CANDU tritium (or otherwise) for commercial operation. Instead, tritium is expected to be produced by neutron interaction with lithium, specifically the isotope lithium-6, in breeding blankets, under the reaction shown in Eq. (7).



The quantity of tritium produced in the breeding blanket must be greater than that used by the fusion reactor, and therefore the reactor must have a TBR (tritium breeding ratio) above 1 in order to achieve “tritium self-sufficiency”. Therefore, although the fuel itself that is required for fusion is tritium, the consumable fuel for a fusion power plant is in fact lithium.

On lithium and deuterium sources alone, it is estimated nuclear fusion power plants could provide the electricity needs of humanity for tens of millions of years (from 14 million [2]

to 23 million years [38]). This leads us to the consideration that the resources for nuclear fusion are *'virtually unlimited.'* Current terrestrial deposits of lithium are estimated at 53 million tons [39]. Given that a nuclear fusion power plant with an electrical output of 1 GWe requires between 10 and 35 tons of lithium over its operational lifetime [2], 2500 1 GWe fusion power plants would require up to 90,000 tons, notwithstanding competition for lithium from advanced technologies such as large scale battery storage. However, it is more complex when considering that many fusion breeder concepts rely on the use of lithium-6 rather than natural lithium. Lithium-6 has an isotopic abundance of only 7.5%, and therefore to obtain 90,000 tons of lithium-6, a total of 1.2 million tons of natural lithium would be required. Even so, this is only around 2% of the current known terrestrial deposits, and a backstop also exists in the form of seawater in which the abundance of lithium and some other key minerals is relatively high. Thus, although production cost would likely increase, lithium could be procured from seawater in the future [40, 41]. Even with competition for lithium, resources appear plentiful for the purposes of fusion, particularly since technological advancements towards D-D and aneutronic fuel cycles may eventually avoid the need for tritium production altogether.

However, resource limitations do exist with other critical materials required for future nuclear fusion reactors. There are potentially significant issues in the supply of helium gas for the cryogenic cooling systems, beryllium for the tritium breeder blanket, and some critical metals that are required for construction of the fusion reactor structure.

Helium resource is expected to be of limited availability for future fusion reactors, and thus improving the efficiency of cooling systems, as well as efforts to reduce and recycle the overall helium inventory, is needed to ensure longevity of the current supply [42]. As above, the lack of tritium available from external sources necessitates the inclusion of a tritium breeder blanket, which will mean lithium as the primary fuel. However, as even enriched lithium-6 tritium breeder blankets are expected to be insufficient to achieve a TBR > 1, beryllium will be used as a neutron multiplier in order to increase the neutron yield and give a higher TBR. Total current global deposits of beryllium are estimated at 100,000 to 150,000 tons, and the quantity of beryllium required per reactor is in the order of 400 tons per GWe. Therefore, current beryllium deposits would be far insufficient to support 2500 GWe of installed fusion reactors using beryllium as the neutron multiplier in the tritium breeder blanket [2]. Fortunately, lead-based tritium breeder blankets, which also provide neutron multiplication and as such offers a substitution option, are also being explored as lead is abundant and cheap. Structural materials, such as vanadium and niobium, are not abundant and although recycling or even extraction from seawater may be possible, alternative metals for alloying should be sought for longer-term fusion reactors.

6. First-Of-A-Kind fusion power plants

6.1. DEMO projects

In anticipation of the successful demonstration of the technical feasibility of nuclear fusion power plants based on the tokamak approach in ITER, many nations around the world are now proposing *Demonstration Nuclear Fusion Power Plants (DEMO)* designs. DEMO will be

based on design, engineering and operational experience of ITER, and is expected to be the First-Of-A-Kind (FOAK) commercially viable fusion power demonstrator in the world (even though it may never produce power to the electricity grid).

SlimCS is a DEMO power plant proposed by JAEA (Japan Atomic Energy Agency, later reformed into QST in 2016). *SlimCS* will have a fusion thermal output of 2.95 GW and an electrical output of 1 GW, and it will assess the economic viability of a large-scale fusion power plant. The reactor is of similar size to ITER, with a major radius of 5.5 m, and an aspect ratio of 2.6 [43]. The Japanese government publicly announced that the decision to construct a DEMO reactor will be made in 2030s, in order to realize the commercialization of fusion energy by the middle of the twenty-first century. As this puts the *SlimCS* schedule in the same timeframe as the operation of ITER, it is uncertain as to what extent ITER will inform *SlimCS*.

The European Union has a dedicated team within EUROfusion which is focused on developing the design of a European version of a DEMO fusion device, *EU DEMO*. Similarly, *EU DEMO* is considered to be the last step before the full-scale commercial roll-out of fusion energy technology. *EU DEMO* is primarily designed to be a pulsed machine but is expected to deliver long pulse durations with only a short dwell time. The expected fusion thermal output is currently envisaged to be in the order of 2 GW, with electrical output at 500 MW, but the design is only in at a conceptual stage [44, 45].

6.2. Innovative approaches by private companies

Due to delays and cost overruns in ITER, questions have been raised over the viability of the ITER pathway as being the best route to fusion energy. This has led to increasing uncertainty over future involvement and project funding, most notably from the United States of America. Such issues with the ITER project have not helped to shift the longstanding perception that commercial fusion is “always 30 years away” [46]. However, alternative fusion energy concepts are also being developed in parallel to the ITER project and are slowly increasing in technological maturity. And such activities have become the subject of increased international interest over recent years. Delays to the public fusion program, combined with novel ideas, disruptive technologies, and an injection of private funding has led to the birth of a number of private-sector start-ups, all looking for a faster route to fusion [47]. Both *Tokamak Energy Ltd* in the UK, and *Commonwealth Fusion Systems*, a spin-out company from MIT in the US, are developing tokamak variants that operate on alternative high-performance plasma regimes that make use of the benefits of HTS magnets [22, 27].

Non-tokamak reactor concepts are looking to explore entirely different configurations and are considering different ways of initiating, heating and sustaining plasmas. The ARPA-E ALPHA program in the United States of America, which has supported a number of start-ups exploring the physics space between inertial and magnetic confinement fusion, with the vision that it may lead to an “easier” route to fusion. This approach is intended to support a number of promising concepts, to spread the risk of failure and therefore at the same time to increase the chances of success [17, 47]. *General Fusion*, a Canadian-based start-up company is developing a reactor based on an entirely novel acoustically-driven system, which will operate in pulse mode [48]. *TAE Technologies* (formerly Tri-Alpha Energy), a US-based start-up, is exploring the possibilities

of liner-driven proton-boron11 fusion, opting to avoid the complications that arise from the D-T fuel cycle, and are already looking at medical applications as a potentially important market [49]. Indeed, of further interest is that *Lockheed Martin* also has an internal “Skunkworks” team dedicated to developing a novel fusion reactor approach. Although few details have been released, the reactor concept is that of a magnetic cusp device, and although patents have been filed, progress towards the realization of fusion energy of the magnetic cusp device is largely being kept secretive [50]. Numerous other fusion start-ups exist, all with the goal of delivering commercial fusion energy. Whether or not these efforts are on the road to success remains to be seen, but a “new fusion race” and the competition it brings is expected to spark technological advancement in a multitude of areas that will likely benefit all in the fusion community, and those outside it, in the pursuit of the holy grail: commercially viable fusion energy.

7. Conclusions: the road to a nuclear fusion power plant

Nuclear fusion has received frequent cynicism, with the longstanding quip that it is “always 30 years away,” in reference to the fact that since the 1970s fusion scientists have continually predicted that fusion energy will take 30 years to become commercial [46]. It appears that this has always been the case, and critics say it always will be. With this in mind, it could appear disingenuous to make the same statement here at the current time, but the realization

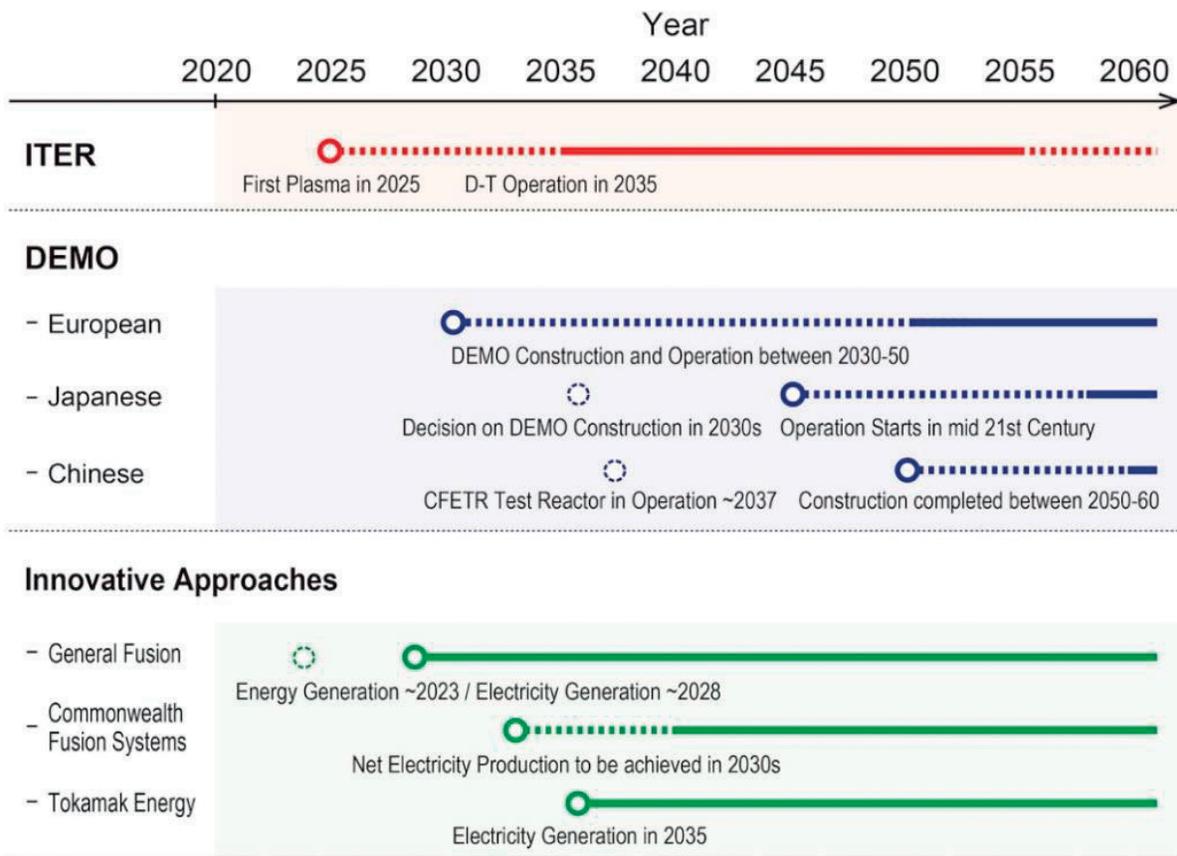


Figure 6. Current timeline for the commercialization of nuclear fusion energy [15, 22, 27, 43, 44, 48].

of a commercial fusion power plant is expected in around 30 years' time. To conclude this overview study, **Figure 6** provides a summary of current efforts, showing key concepts and expected milestones, on the pathway to commercial nuclear fusion energy.

The result of this review study highlights the current plans for the development of fusion to deliver on the promise of fusion energy. Current plans to realize fusion power are continuously updated, however should be treated with caution, as they are subject to uncertainties, unknown obstacles to technological progression and resource limitations in funding and manpower; all of which may limit the ability to achieve future goals in a timely manner. At the current time, however, it is expected that fusion energy will become a reality in less than 30 years. Every effort to ensure this timescale is realized should be made so that fusion can fulfill its potential and make the much-needed impact in global energy.

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References

- [1] Burbidge EM, Burbidge GR, Fowler WA, Hoyle F. Synthesis of the elements in stars. *Reviews of Modern Physics*. 1957;**29**(4):547. DOI: 10.1103/RevModPhys.29.547
- [2] Bradshaw AM, Hamacher T, Fischer U. Is nuclear fusion a sustainable energy form? *Fusion Engineering and Design*. 2011;**86**(9-11):2770-2773. DOI: 10.1016/j.fusengdes.2010.11.040
- [3] Ueda Y, Inoue T, Kurihara K. Intelligible seminar on fusion reactors—(1) Introduction to fusion reactors. *Journal of the Atomic Energy Society of Japan*. 2004;**46**(12):27-34

- [4] Armaroli N, Balzani V. The future of energy supply: Challenges and opportunities. *Angewandte Chemie International Edition*. 2007;**46**(1-2):52-66. DOI: 10.1002/anie.200602373
- [5] Browne E, Dairiki JM, Doebler RE. Table of Isotopes. Fort Belvoir, VA: National Standard Reference Data System; 1978
- [6] Oliphant M, Harteck P, Rutherford L. Transmutation effects observed with heavy hydrogen. *Proceedings of the Royal Society of London Series A, Containing Papers of a Mathematical and Physical Character*. 1934;**144**(853):692-703. DOI: 10.1098/rspa.1934.0077
- [7] Arnoux R. Who invented fusion Saint-Paul-lès-durance: ITER Organization [Internet]; 2014. Available from: <https://www.iter.org/newsline/-/1836> [Accessed: 2018-06-01]
- [8] Braams CM, Stott PE. Nuclear Fusion: Half a Century of Magnetic Confinement Fusion Research. Boca Raton, FL: CRC Press; 2002. DOI: 10.1088/0741-3335/44/8/701
- [9] ITER. ITER Tokamak and Plant Systems [Internet]. 2016. Available from: <https://www.iter.org/album/media/> [Accessed: 2018-06-02]
- [10] Atzeni S, Meyer-Ter-Vehn J, Meyer-ter-Vehn J. The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter. Oxford, UK: Oxford University Press; 2004
- [11] National Physical Laboratory. Kaye&Laby. Tables of Physical & Chemical Constant, Chapter 4, Section 4.7 [Internet]. Available from: http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_4.html [Accessed 2018-06-04]
- [12] Torrisi L. Ion acceleration and DD nuclear fusion in laser-generated plasma from advanced deuterated polyethylene. *Molecules*. 2014;**19**(10):17052-17065. DOI: 10.3390/molecules191017052
- [13] Kamada Y. Intelligible seminar on fusion reactors—(2) Introduction of plasma characteristics for fusion reactor design. *Journal of the Atomic Energy Society of Japan*. 2005; **47**(1):45-52
- [14] Lawson JD. Some criteria for a power producing thermonuclear reactor. *Proceedings of the Physical Society Section B*. 1957;**70**(1):6. DOI: 10.1088/0370-1301/70/1/303
- [15] Donné AJH, Federici G, Litaudon X, McDonald DC. Scientific and technical challenges on the road towards fusion electricity. *Journal of Instrumentation*. 2017;**12**(10):C10008. DOI: 10.1088/1748-0221/12/10/C10008
- [16] Nuclear Fusion Research in the World—The Frontier of Nuclear Fusion Research: NIFS/SOKENDAI Department of Fusion Science [Internet]. Available from: <http://soken.nifs.ac.jp/wp/en/about/> [Accessed 2018-06-04]
- [17] ARPA-E. ALPHA Program Overview United States Department of Energy [Internet]. 2015. Available from: https://arpa-e.energy.gov/sites/default/files/documents/files/ALPHA_ProgramOverview.pdf [Accessed 2018-06-10]

- [18] Kikuchi M. A review of fusion and Tokamak research towards steady-state operation: A JAEA contribution. *Energies*. 2010;**3**(11):1741-1789. DOI: 10.3390/en3111741
- [19] Stott P. The feasibility of using D–3He and D–D fusion fuels. *Plasma Physics and Controlled Fusion*. 2005;**47**(8):1305. DOI: 10.1088/0741-3335/47/8/011
- [20] Nuttall WJ. A trip to 'Fusion Island' [Internet]. 2005. Available from: <https://www.theengineer.co.uk/issues/31-october-2005/a-trip-to-fusion-island/> [Accessed 2018-06-10]
- [21] Pearson RJ, Bluck MJ, Murphy ST. A symbiotic approach to compact fission and fusion reactors. *ANS Transactions*. 2017;**117**(1):378-381
- [22] Sykes A, Costley A, Windsor C, Asunta O, Brittles G, Buxton P, et al. Compact fusion energy based on the spherical tokamak. *Nuclear Fusion*. 2017;**58**(1):016039. DOI: 10.1088/1741-4326/aa8c8d
- [23] Locatelli G, Boarin S, Pellegrino F, Ricotti ME. Load following with small modular reactors (SMR): A real options analysis. *Energy*. 2015;**80**:41-54. DOI: 10.1016/j.energy.2014.11.040
- [24] You JH, Mazzone G, Visca E, Bachmann C, Autissier E, Barrett T, et al. Conceptual design studies for the European DEMO divertor: Rationale and first results. *Fusion Engineering and Design*. 2016;**109**(111):1598-1603. DOI: 10.1016/j.fusengdes.2015.11.012
- [25] Stork D, Zinkle SJ. Introduction to the special issue on the technical status of materials for a fusion reactor. *Nuclear Fusion*. 2017;**57**:092001. DOI: 10.1088/1741-4326/aa69e4
- [26] Abdou M, Morley NB, Smolentsev S, Ying A, Malang S, Rowcliffe A, et al. Blanket/first wall challenges and required R&D on the pathway to DEMO. *Fusion Engineering and Design*. 2015;**100**:2-43. DOI: 10.1016/j.fusengdes.2015.07.021
- [27] Whyte D, Minervini J, LaBombard B, Marmor E, Bromberg L, Greenwald M. Smaller & sooner: Exploiting high magnetic fields from new superconductors for a more attractive fusion energy development path. *Journal of Fusion Energy*. 2016;**35**(1):41-53. DOI: 10.1007/s10894-015-0050-1
- [28] Federici G, Kemp R, Ward D, Bachmann C, Franke T, Gonzalez S, et al. Overview of EU DEMO design and R&D activities. *Fusion Engineering and Design*. 2014;**89**(7):882-889. DOI: 10.1016/j.fusengdes.2014.01.070
- [29] Wu Y, Team F. Conceptual design activities of FDS series fusion power plants in China. *Fusion Engineering and Design*. 2006;**81**(23-24):2713-2718. DOI: 10.1016/j.fusengdes.2006.07.068
- [30] Gulden W, Ciattaglia S, Massaut V, Sardain P. Main safety issues at the transition from ITER to fusion power plants. *Nuclear Fusion*. 2007;**47**:S415. DOI: 10.1088/0029-5515/47/9/C01
- [31] Massimo Z, Kuigi C, Vladimir K, Boris K, Raffaella T. Fusion power plants, fission and conventional power plants. Radioactivity, radiotoxicity, radioactive waste. *Fusion Engineering and Design*. 2018 (in press). DOI: 10.1016/j.fusengdes.2018.05.049

- [32] Goldston RJ, Glaser A, Ross AF. Proliferation Risks of Fusion Energy: Clandestine Production, Covert Production, and Breakout. 9th IAEA Technical Meeting on Fusion Power Plant Safety. Vienna: IAEA; 2009
- [33] Gsponer A, Hurni J-P. ITER: The International Thermonuclear Experimental Reactor and the Nuclear Weapons Proliferation Implications of Thermonuclear Fusion Energy Systems. Geneva: Independent Scientific Research Institute; 2008
- [34] Perrault D. Safety issues to be taken into account in designing future nuclear fusion facilities. *Fusion Engineering and Design*. 2016;**109**(111):1733-1738. DOI: 10.1016/j.fusengdes.2015.10.012
- [35] Nugent D, Sovacool BK. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy*. 2014;**65**:229-244. DOI: 10.1016/j.enpol.2013.10.048
- [36] Uchiyama Y. Life cycle analysis of power generation systems. CRIEPI Research Report. 1995;**Y94009**:12-31
- [37] Tokimatsu K, Yamaji K, Katsurai M, Hondo H. Energy analysis and carbon dioxide emission of tokamak fusion power reactors. *Purazuma, Kaku Yugo Gakkai-Shi*. 1998;**74**(1):54-66. DOI: 10.1016/S0920-3796(00)00157-5
- [38] Text—Fusion Reactors—Tokamak Reactor Designs and their Basis on Plasma Physics and Reactor Technology. JSPF, editor. Nagoya: JSPF; 2011.
- [39] USGS. Lithium 2018 [Internet]. 2018. Available from: <https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2018-lithi.pdf> [Accessed 2018-06-10]
- [40] Ooi K. Technology on the lithium recovery from seawater (1) adsorbent for lithium. *Bulletin of the Society of Sea Water Science, Japan*. 1997;**51**(5):285-288
- [41] Nobukawa H. Technology on the lithium recovery from seawater (2) extraction system and simulation. *Bulletin of the Society of Sea Water Science, Japan*. 1997;**51**(5):289-292
- [42] Nuttall WJ, Clarke R, Glowacki B. *The Future of Helium as a Natural Resource*. Abingdon: Routledge; 2012
- [43] Tobita K, Nishio S, Enoeda M, Nakamura H, Hayashi T, Asakura N, et al. Conceptual Design of the SlimCS Fusion DEMO Reactor. Japan Atomic Energy Agency: Naka; 2010
- [44] Federici G, Biel W, Gilbert M, Kemp R, Taylor N, Wenninger R. European DEMO design strategy and consequences for materials. *Nuclear Fusion*. 2017;**57**(9):092002. DOI: 10.1088/1741-4326/57/9/092002
- [45] EFDA. *Fusion Electricity: A Roadmap to the Realisation of Fusion Energy*. Culham: European Fusion Development Agreement; 2012
- [46] Herrera-Velázquez JE. Nuclear Fusion as an Energy Option for the 21st Century. In: Klapp J, Cervantes-Cota JL, Chávez Alcalá JF, editors. *Towards a Cleaner Planet*. Berlin: Springer; 2007. p. 405-419. DOI: 10.1007/978-3-540-71345-6_25

- [47] Pearson RJ, Antoniazzi AB, Nuttall WJ. Tritium supply and use: A key issue for the development of nuclear fusion energy. *Fusion Engineering and Design*. 2018 (in press). DOI: 10.1016/j.fusengdes.2018.04.090
- [48] Laberge M. General fusion development program for acoustic magnetized target fusion. *Journal of Plasma Fusion Research*. 2017;**93**(1):32-37
- [49] Binderbauer M, Tajima T, Steinhauer L, Garate E, Tuszewski M, Schmitz L, et al. A high performance field-reversed configuration. *Physics of Plasmas*. 2015;**22**(5):056110. DOI: 10.1063/1.4920950
- [50] McGuire TJ. Magnetic field plasma confinement for compact fusion power. U.S. Patent No. 9,947,420. 17; 2018

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