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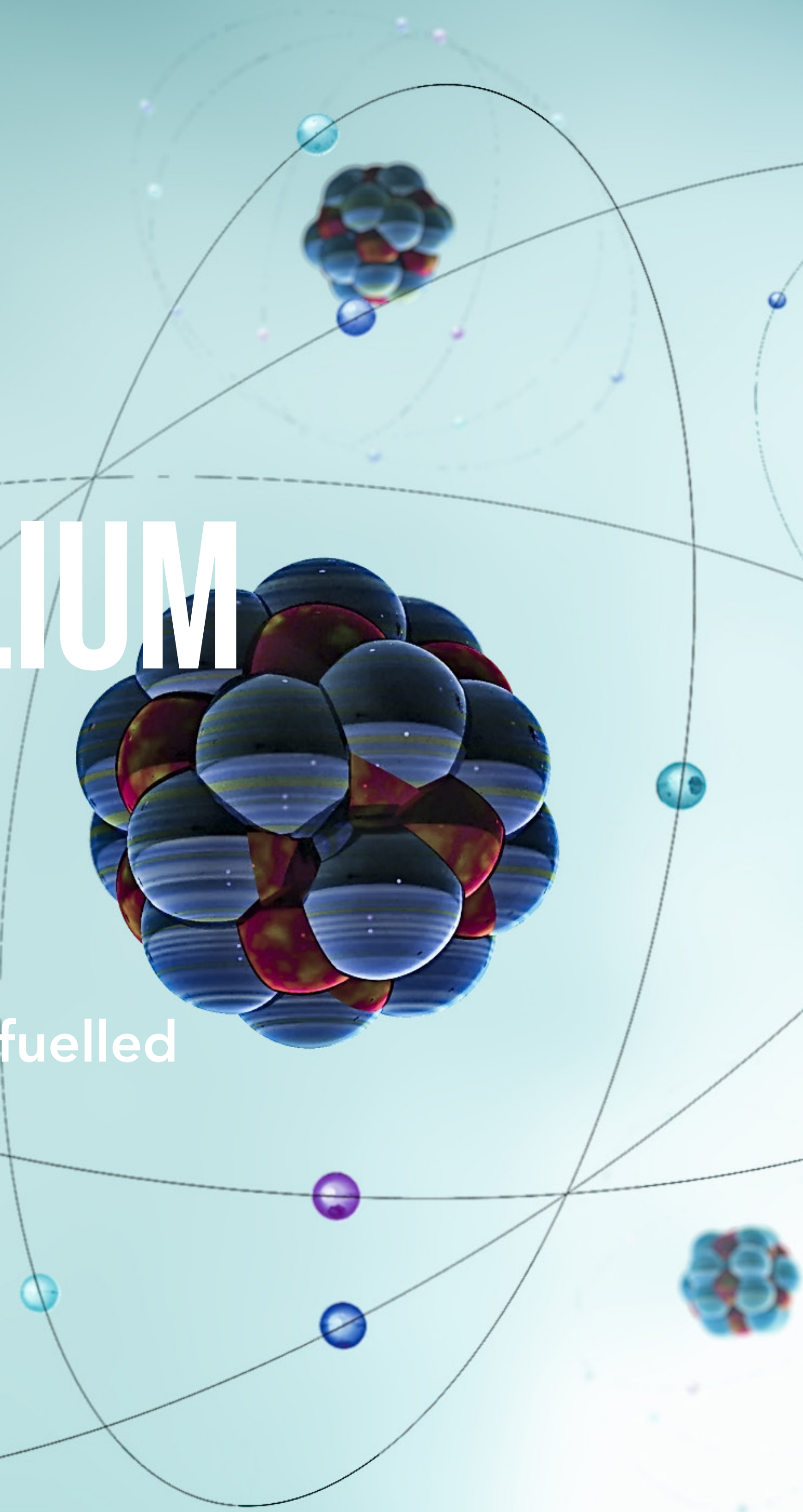

Prospects for ^{3}He-fuelled nuclear fusion

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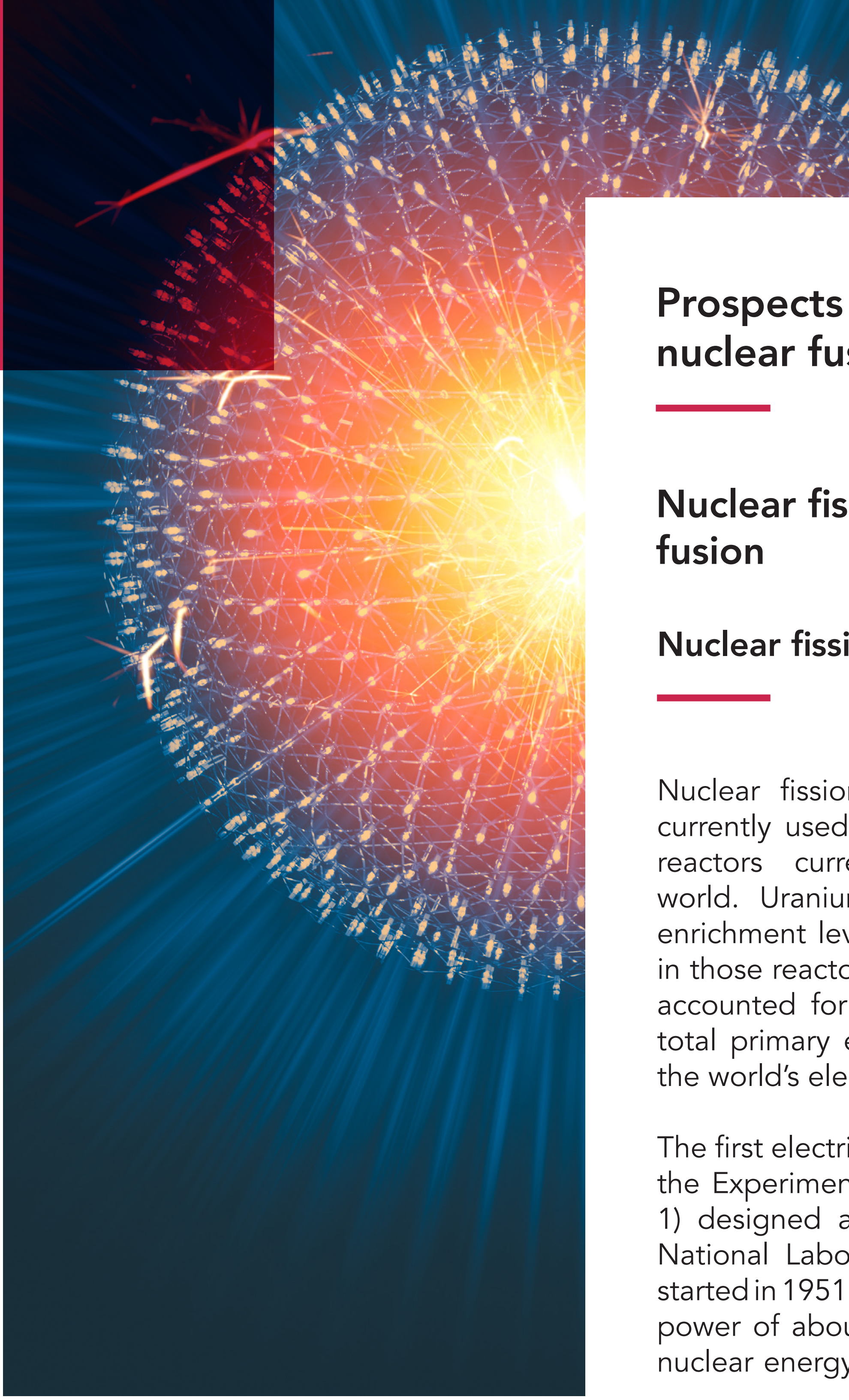


Prospects for ^{3}He-fuelled nuclear fusion

Nuclear fission and nuclear fusion

Nuclear fission

Nuclear fission is the process that is currently used in the 400 or so nuclear reactors currently operating in the world. Uranium-235 (^{235}U), at different enrichment levels, is the main fuel used in those reactors. In 2019, nuclear fission accounted for about 4% of the world's total primary energy and about 10% of the world's electricity[1].

The first electricity producing reactor was the Experimental Breeder Reactor (EBR-1) designed and operated at Argonne National Laboratory in the USA, which started in 1951. It produced a net electrical power of about 200 kW. Following this, nuclear energy experienced a very rapid

A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy

deployment (fig. 1) in the period 1954-1990 with 418 reactors put in operation during that period- a deployment rate which to date has not been surpassed by other energy technologies[2].

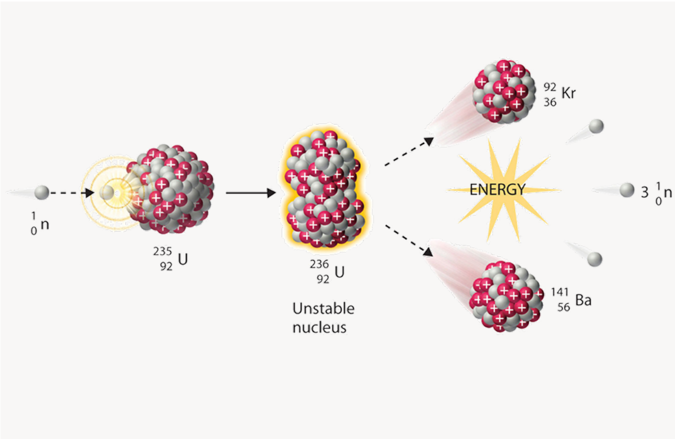
This deployment did, however, stop abruptly after that with only about 20 reactors going into operation between 1990 and 2000. This is in part due to public concerns after the Three Miles Islands (1979) and Chernobyl (1986) accidents, and results in having an impact on public acceptance[3,4].

Nuclear fusion

Nuclear fusion is the process by which two or more atoms combine to form one (or more) heavier atoms. This is in essence the opposite of the fission process whereby heavy atoms are split into lighter elements. The two processes are similar in that they both release energy. This is a manifestation of the famous mass-energy equivalence.

The idea of using nuclear fusion to generate energy was born in 1920 when Sir Arthur Eddington suggested that stars get their energy from the fusion of hydrogen.

"A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy which, it is known exists



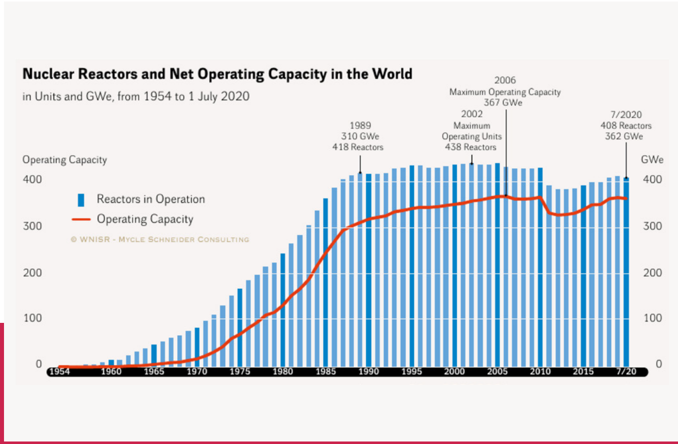
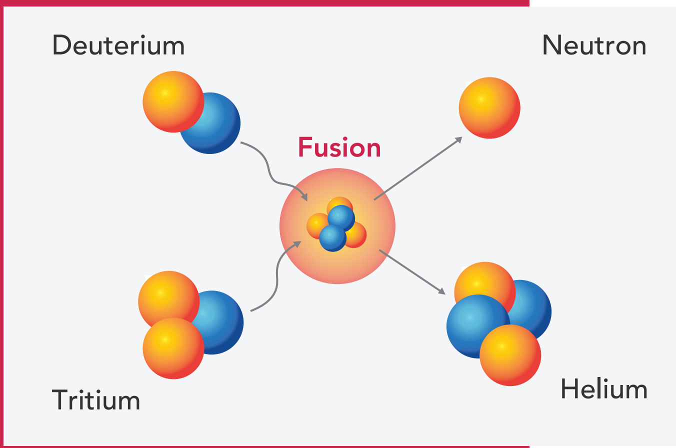


Figure 1: (left) the nuclear fission process used in nuclear reactors involves the splitting of fissile material (uranium) to produce lighter atoms and neutrons (Source). (right) Evolution of the number of operating nuclear reactors in the world during the period 1954-2020 (Source)

abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped."



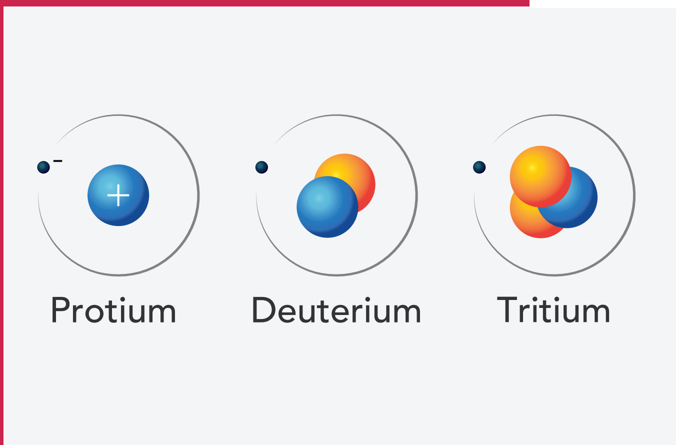


Figure 2: (top) Illustration of the deuterium tritium fusion reaction. Deuterium and tritium fuse to form a helium atom and a neutron. (bottom) There are three isotopes of hydrogen which have the same number of protons but different numbers of neutrons.

The Sun, for example, fuses about 627 million tons of hydrogen (H) into helium (He) every second to produce 4×10^{26} J of energy. This is roughly one million times the world's total primary energy use in one year (5×10^{20} J).

About a 100 years later, the famous quote from Eddington still nicely summarizes the ongoing efforts to master fusion for energy production. Fusion research started after World War II for both military and energy applications. Almost 70 years later, fusion energy is still as elusive as this famous joke summarizes it: "Fusion is 30 years away… and will always be…"

While radioactive decay can happen naturally for some atoms, nuclear fusion requires bringing atoms sufficiently close enough together (in the femtometer range- 10^{-15}m) for the attractive strong nuclear force, which acts only on very short distances, to allow the heavier particle to form (see fig. 2 top for the deuterium-tritium reaction).

However, since nuclei are positively charged (fig. 2 bottom) there is a strong repulsive force between the nuclei which acts against the fusion process. Counteracting this repulsion requires particles to collide with high energy, which, in the field of fusion, means high temperatures.

Heating the fuel to extremely high temperatures is therefore required to induce fusion. The fuel is then in the form of a plasma (box 1). For that reason, a fusion reactor should be seen as a power amplifier.

Box 1

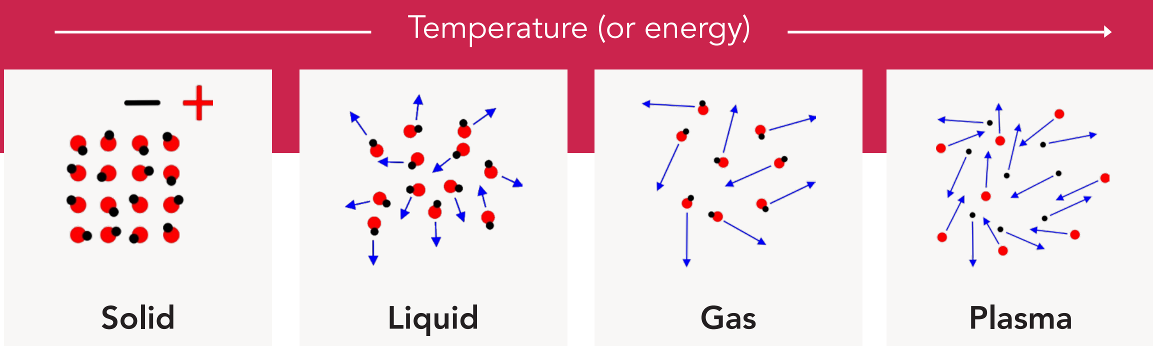
What is a plasma?

The plasma state is often referred to as the fourth state of matter- after solid, liquid and gas- because when heated a gas forms a plasma. As the temperature is increased, the particles have enough energy for the electrons to be able to leave the nuclei.

A plasma is therefore a mixture of electrically charged particles, the electrons are charged negatively, and the ions are charged positively, and non-ionized neutral particles.

Overall a plasma is neutral, there are as many negative as positive charges. Plasmas are typically characterized by their density (number of particles per unit of volume), temperature, and ionization degree (fraction of particles which are ionized).

The temperature of the electrons and ions can be different, this is the case in many applications because electrons are easier to heat and they do not transfer their energy to the ions very efficiently because of the high mass difference. When it is the case, it is necessary to indicate whether the mentioned temperature is for the ions or for the electrons.
Plasmas can be used in many applications such as surface treatment, sterilization, materials deposition, etc.



The power amplification factor, or fusion gain, Q, is defined as the ratio of the produced fusion power to the injected power (to heat the plasma):

$$Q = \frac{fusion\ power}{injected\ power}$$

If Q=1, the produced power equals the injected power, and no net power is generated- which obviously is not too useful for a reactor. A fusion reactor needs to produce more energy than is required to heat the fuel. Q needs to be much higher than 1. A value of around 30 to 50 is required to produce net electricity at a competitive cost[5,6].

The figure of merit to characterize the performance of fusion and define the required conditions for net energy production is the so-called triple product of plasma temperature (T), density (n) and energy confinement time* (τ_E).

The condition required to reach ignition, known as the Lawson criterion, is mainly

* The energy confinement time measures the rate at which the confined plasma loses energy to its environment. It is a measure of the thermal insulation of the plasma.

that the triple product $n \times T \times \tau_E$ needs to be higher than a given value.

The Lawson criterion shows that in principle different strategies can be used to reach the required conditions, and two main schemes have been researched over the years:

- Magnetic confinement: the plasma is confined by strong magnetic fields, has relatively low densities (much lower than air density), and the confinement time is a few seconds. This is the approach followed by ITER, the next step fusion device currently being built in France and whose mission is to demonstrate net fusion energy production.
- Inertial confinement: the fuel is compressed and heated by intense but very short laser pulses giving rise to extreme densities (about 100 times that of lead), albeit with confinement times of the order of nanoseconds. This is the approach followed at the National Ignition Facility (NIF).

The reason that the fusion quest has proceeded over such a long period is that it presents many very attractive characteristics for a future energy source[7]. Amongst those advantages are[8]:

- Low carbon footprint
- High energy density of the fuel (in joules per kg)
- High power density of a power plant (in watts per m^2)
- No risk of meltdowns
- Strongly reduced possibilities of proliferation
- Fuel in abundance
- No long-lived high activity waste

Key Highlights

Nuclear fusion is a promising technology for abundant and safe energy with very low greenhouse gas emissions. It has unfortunately proven very hard to master and the prospect of viable commercial deployment is still elusive.

The prospects of using helium-3, mined from the Moon for fusion, energy on Earth is often mentioned in long-term scenarios for space resource exploitation.

Using helium-3 for fusion is unfortunately very difficult and requires conditions not yet demonstrated.

We show that this technology would only be considered for a second or third generation of fusion reactors.

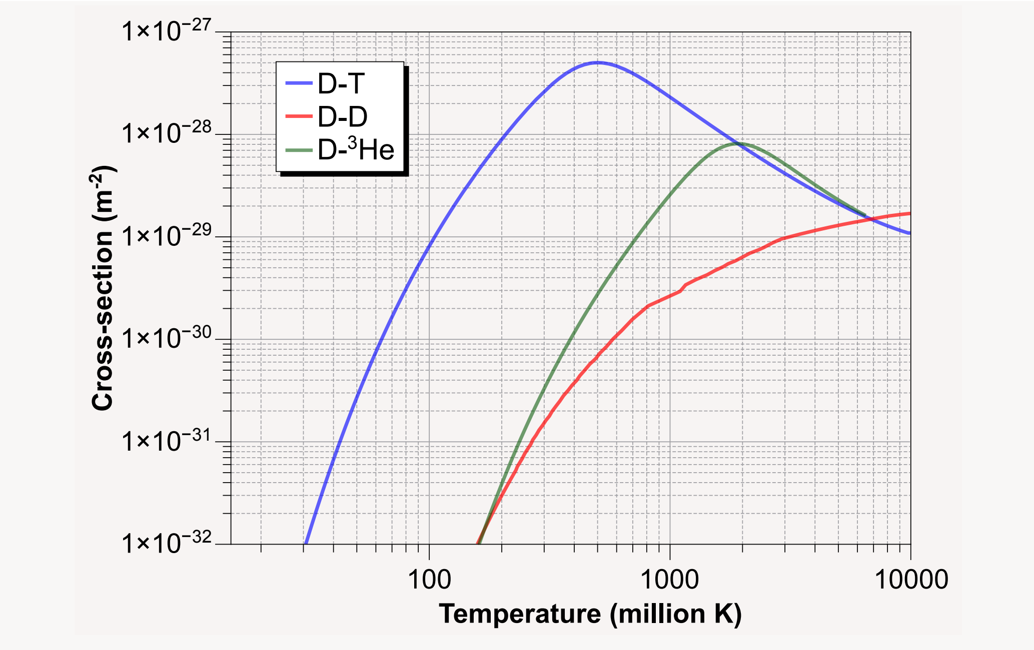


Figure 3: Reaction rates (or probability of reactions) of different candidate fusion reactions as a function of the ion temperature. N.B. the scale is logarithmic

Different fusion schemes

Candidate fusion reactions

Several reactions can in theory be considered for fusion energy production. Candidate reactions need to release energy and to involve light elements (as the electrostatic repulsion between nuclei increases with the number of protons). The exhaustive list of the most interesting reactions is given below:

$$D + T \rightarrow {}^4He + n + 17.6MeV \ (1)$$
$$D + D \rightarrow H + T + 4.03MeV \ (2a) \ 50\%$$
$$D + D \rightarrow n + {}^3He + 3.27MeV \ (2b) \ 50\%$$
$$D + {}^3He \rightarrow H + {}^4He + 18.35MeV \ (3)$$

Most reactions involve isotopes of hydrogen. One can distinguish two classes of reactions depending on whether they lead to neutron formation or not. The latter will be referred to as aneutronic fusion. The importance of neutron production will be discussed later. Some reactions are easier to achieve than others because they have a higher probability of occurring at a given temperature.

This is characterized by the reaction rate; the number of reactions per second (fig. 3). By far, the easiest reaction involves deuterium and tritium.

The reaction rate peaks at around 810 million °C*. As a result, most (if not all) fusion research currently deals with this reaction scheme. Other reactions require much higher temperatures.

* In plasma physics, one usually calls temperature the product k_BT (k_B is the Boltzman constant), the kinetic particle energy, which is expressed in electron-volts (eV). 1eV=11600 K

D-T fusion: status and challenges

For the D-T reaction, the high energy neutron produced by the reactor counts for 80% of the energy, while the helium nucleus, known as an alpha particle, counts for the remaining 20%. Being electrically charged the latter is confined to the plasma and heats it through collisions. A burning plasma, such as in a reactor, is defined as a plasma that is mainly self-heated by the fusion reaction i.e. that the heating through alpha particles is higher than the externally applied heating.

Most (if not all) fusion research focuses on the D-T scheme. Deuterium is naturally present in water with a natural abundance of 0.015% and can be produced by distillation. Seawater provides a plentiful source of fuel which has the advantage of being widely distributed since about 70% of the Earth's surface is covered by oceans.

Tritium is radioactive and has a half-life of 12.3 years (decaying in ^3He) and therefore does not exist naturally on Earth in large quantities. A very small quantity (0.2 kg/year) is produced through interaction between cosmic radiation and nitrogen-14 in the atmosphere. The natural tritium inventory on Earth is estimated at about 3.5 kg[9]. Most tritium is produced in nuclear reactors using heavy water as a moderator, such as the CANDU reactors in Canada. A 600 MWe (electric) CANDU reactor produces about 150 g of tritium per year.

The estimated world T inventory is about 30 kg while a 500 MWth fusion reactor will consume about 28 kg of T per year (assuming operation at full capacity)[10]. To solve the issue of the tritium shortage, it is envisaged that tritium will be bred in future fusion reactors using lithium through the following reaction[11]:

$$^6Li + n \rightarrow He + T + 4.78\ MeV$$

The plasma in a fusion reactor will be surrounded by a tritium breeding blanket which will contain beryllium acting as a neutron multiplier and then lithium for tritium production (fig. 4). The produced tritium will then have to be extracted and used to fuel the reactor.

A fusion reactor will need to have a breeding ratio of 1.05, i.e. produce 5% more tritium than it consumes, in order to be self-sufficient and provide tritium for future reactors[12]. The concept of tritium breeding has not been demonstrated on a large scale and ITER will test a number of concepts during its operations[13]. The necessity for tritium breeding represents a significant technical complexity for the engineering of future reactors[14–16].

The necessity for tritium breeding represents a significant technical complexity for the engineering of future reactors.

In fact, the fuel for future fusion reactors based on the D-T scheme is deuterium and lithium rather than deuterium and tritium. In terms of resources, currently the accessible resources of lithium could provide for today's consumption levels for at least 2800 years, but the competition with lithium use for batteries could make this number significantly smaller[17].

Recovery of lithium from seawater[18] would increase the known resources by several orders of magnitude but the environmental and energy costs of such extraction need to be studied in more detail[17]. To date, there is no study of the energy return of such schemes. A more stringent limit might come from beryllium which is required for breeding[19] or from the materials required to manufacture parts of the reactor.

Another challenge with D-T fusion is the creation of a very energetic neutron which will continuously bombard the material structures surrounding the fusion plasma[20,21]. Those neutrons are much more energetic than those produced in fission reactors. The other difference is that materials in a D-T fusion reactor would be bombarded by an accumulated number of neutrons far in excess of that which the materials in fission reactors currently experience.

Energetic neutrons slow down in materials, losing their energy through collision with atoms, thereby creating displacement damage and heating the materials. That heat is extracted to produce electricity. The neutrons can produce gaseous species (hydrogen and helium) in the materials, which embrittle them over time[22]. The development of materials which can sustain those harsh irradiation conditions is a recognized challenge for the success of fusion and is the topic of active investigations[22].

One difficulty, however, is that to date no source of neutrons reproducing the relevant conditions in order to validate material choices exists[23]. In addition to damage, the high energy neutrons produce solid transmutation products and

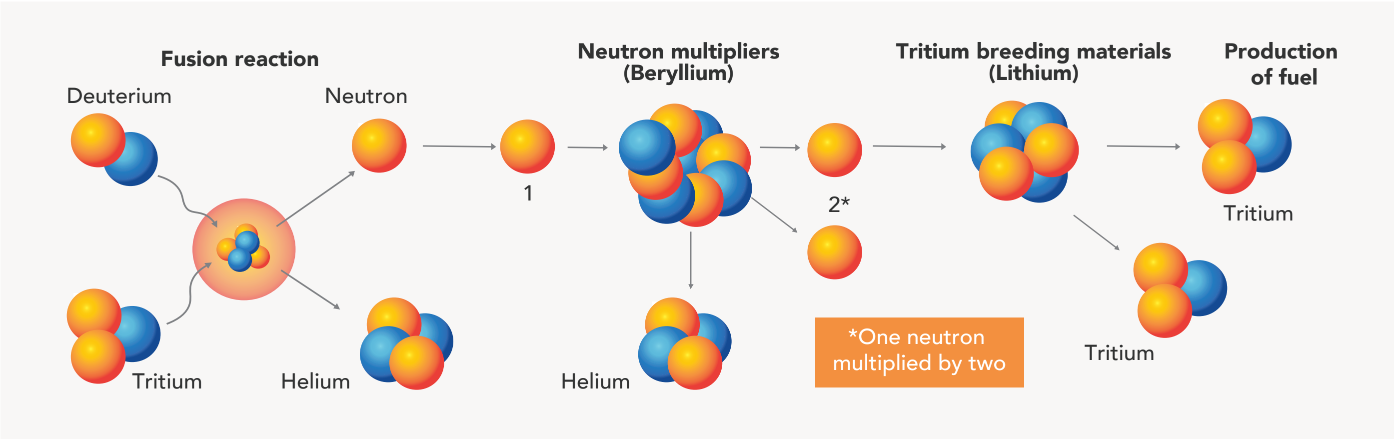


Figure 4: Conceptual representation of the tritium breeding concept. The neutron produced by the fusion reaction bombards the blanket which contains beryllium. Beryllium acts as a multiplier: an incoming neutron reacts with beryllium to form helium and 2 neutrons. Those 2 neutrons then react with the lithium-containing breeder to form tritium. (Source)

activate materials. Although fusion will not produce long-lived high activity waste, recent calculations show that Eurofer-97 (the current structural material of choice for the planned demonstration power plant DEMO) will activate and produce intermediate level waste which will require storage[24].

This is problematic given the large quantity of steel used as structural material for the vacuum vessel or the blanket- of the order of 1200-1500 tons[25].

Aneutronic fusion

The complications with the tritium breeding and the high energy neutrons have motivated the ideas of using aneutronic reaction schemes. The possible candidates are the D-^{3}He and the p-^{11}B schemes. Comparing their reactivities, the former is by far more attractive[26] because it requires lower temperatures than the p-^{11}B reaction, although it should be stressed that both of them require much higher temperatures and triple product than the D-T scheme. There is still some controversy on the feasibility of the p-^{11}B scheme[27,28]. This principle is, however, pursued in private ventures such as TAE and H11B.

Thanks to the lack of neutrons, aneutronic fusion schemes would offer the possibility to use non-thermal energy conversion schemes such as direct conversion[29], where the energy of the charged particles in the plasma would be converted directly to electricity without having to go through vapor generation to activate turbines. In theory, this would allow a higher conversion efficiency of fusion power to electricity, and thus potentially improve

Box 2

Density matters

For fuels, a very important property is the energy density i.e. the amount of energy in 1 kg of fuel. One of the reasons that oil (and its derivatives) is used for transportation (and so hard to replace) is that it is both dense (typically 60% more than coal) and liquid so that it can be easily transported. Because nuclear energy uses the energy of the atoms, the nuclear fuel is several orders of magnitude denser than fossil fuels. A kilogram of deuterium-tritium contains as much energy as 10,000 tons of coal.

FUSION
1 kilogram

FISSION FUEL
100 kilograms

NATURAL GAS
6,000,000 kilograms

COAL
10,000,000 kilograms

the economics of a fusion reactor.

Because of its higher reactivity, the D-^{3}He reaction has been the most investigated aneutronic fusion scheme[30]. Interest for it has also been boosted by the analysis of regolith samples brought back from the Moon, which revealed that the Moon could contain vast quantities of ^{3}He[31]. In the following we will quickly review its possibilities and limitations.

^{3}He-fuelled fusion

^{3}He as a fuel

The use of ^{3}He as a fuel for fusion energy production has long been considered as an alternative to the D-T scheme[32] although the lack of significant reserves was already known at the time. ^{3}He is produced on Earth from the interaction of cosmic rays with lithium and from the radioactive decay of tritium. ^{3}He is known to leak from the Earth's mantle but at a rate of not even a few kilograms per year. The natural abundance of ^{3}He is about 300 atomic parts per million compared to ^{4}He.

The US currently possesses around 25 kg of ^{3}He through its strategic reserve of helium-4. This National Helium Reserve was established in 1925 to secure supplies for airships and later for cryogenic cooling during the space race. The production through radioactive decay of tritium, both from military and civilian sources of tritium, amounts to an annual production of about 18 kg/year[33].

One could also consider producing ^{3}He from the decay of tritium, whose production would need to be significantly upscaled, or through the reaction of deuterium with neutrons. As mentioned already, tritium is a limiting factor for the D-T scheme, so there is little prospect of producing ^{3}He on a large scale using this method. Similarly, producing ^{3}He through deuterium would require abundant neutron sources, displacing the issue of material activation from the fusion reactor to the ^{3}He producing plant.

To circumvent the resource issue, the idea of making use of lunar resources which are known to be much more abundant has repeatedly been proposed. Having no magnetosphere, the Moon surface is bombarded by the solar wind which contains ^{3}He created through fusion reactions on the sun. ^{3}He has thus accumulated on the Moon for billions of years. The ^{3}He content on the Moon's surface has been characterized by analyses of lunar samples brought by the Apollo and Luna missions.

From those analyses, the ^{3}He abundance in the regolith is estimated at about 30 micrograms per gram of regolith[33,34].

Thanks to the lack of neutrons, aneutronic fusion schemes would offer the possibility to use non-thermal energy conversion schemes

Taking a depth of 3 meters into account (^3He is generated by energetic particles and therefore concentrated near the surface), the lunar reserve would be of the order of 1 million tons, corresponding to 600 ZJ (1 zettajoule=10^{21} joules) if used in fusion reactors, i.e., about 1000 times the total primary energy consumption in the world each year. Detailed studies using remote sensing have identified promising mining sites where the ^3He concentration is higher[35].

Mining ^3He on the Moon is therefore often mentioned as an interesting activity which could justify a business model by itself to go back to the Moon. Technically, recovering ^3He from the lunar regolith requires heating it to a temperature of between 300°C and 900°C, with 700°C being sufficient to recover most of the gas[31]. Research is ongoing to develop potential methods for ^3He mining and recovery[36].

Estimating the cost of mining ^3He on the Moon and transporting it to Earth is highly speculative as much of the required infrastructure does not exist yet. To justify the likely high costs of such a venture, it is useful to bear in mind that the energy density of ^3He is orders of magnitude higher than that of crude oil. In energy terms, 1 ton of ^3He is roughly equivalent to 100 million barrels of crude oil*. The latter has traded at an average of 50$/barrel over the last 5 years. In terms of energy price, assuming an equivalent service, this puts an equivalent price of ^3He at 5 billion $ per ton.

For reference, the launching costs from Earth to space are currently in the range of 10 000 $/kg (or 10 million $ per ton) for the low Earth orbit. Going to the Moon and back would obviously be much more expensive, and at this stage it is difficult to foresee what the cost would be. A full infrastructure would need to be developed to allow for mining on the Moon and transportation back to Earth and even with such a high possible price for ^3He, the economic viability is not guaranteed.

It is important to stress that the deuterium and lithium resources on Earth are so abundant that the case to mine on the Moon will be difficult to make from an economic point of view.

Technical feasibility

A few points need to be considered regarding the technical feasibility of the D-^3He fusion scheme. First, although the reaction itself does not produce neutrons, some D-D reactions can happen (reactions 2a and 2b), forming T and neutrons in the process. Since the D-T reaction has a much higher reactivity, D-T reactions will compete with the D-^3He reaction. To reduce the neutron production it has been suggested to use a ^3He rich mixture (15% D, 85% ^3He)[37]. Even if neutrons are produced, the significantly reduced neutron activation would strongly increase the material lifetime.

Besides the temperature requirements for the D-^3He reaction, the technical feasibility of this scheme will depend on

* Assuming that the energy density of crude oil is 42GJ/ton

the underlying plasma physics which will dictate which confinement scheme could be applied. A few parameters need to be defined here to guide the discussion.
In a magnetically confined plasma, an important parameter is β, the ratio of the plasma pressure p to the magnetic pressure p_B:

$$\beta = \frac{p}{p_B} \sim \frac{nT}{B^2}$$

In a tokamak*, β is typically of the order of a few percent[38], while so-called spherical tokamaks (which have lower aspect ratios) can achieve higher values with about 40% demonstrated in the START tokamak[39]. There is a limit on the plasma pressure which can be confined. Other confinement devices such as the field reversed configuration (FRC) could attain much higher values[40].

For a given magnetic field, and for temperatures maximizing the reaction rates (13 keV for D-T and 60 keV for D-^{3}He), the product $\beta\tau_E$ would need to be 24 times higher for a D-^{3}He fueled reactor than for a D-T fueled reactor for both to reach ignition. The ratio increases to 61 times for a 15% D-85% D-^{3}He mixture[29].

Another interesting parameter for a reactor is the volume averaged power density which scales as the square of the plasma pressure p^2 and influences the possible cost of electricity. To get the same electricity producing power density, a 50%

* A tokamak is a magnetic device where the plasma is confined in the shape of the donut using a combination of strong magnetic fields. It is currently the leading configuration for a fusion reactor, and is the model for ITER, due to its superior performance.

Even if neutrons are produced, the significantly reduced neutron activation would strongly increase the material lifetime.

D-50% ^{3}He fuel mixture would require a plasma pressure 9 times higher than a D-T reactor, while this ratio increases to 14 times for a 15% D-85% D-^{3}He mixture.

An illustration of the much more demanding requirements on the plasma physics side can be found in the design study by Emmert et al[41]. In the 1980s, plans for a big tokamak to be built in Europe were discussed to succeed the Joint European Torus (JET, currently the world largest tokamak). The device was called NET (Next European Torus) and aimed at demonstrating significant fusion power production (around 600 MW)[42]. Its objectives were close to those of the latest version of ITER. Emmert's study showed that while NET would achieve Q higher than 10 with D-T, it would hardly achieve a gain of 1 with D-^{3}He. A factor 10 difference in performances between the two fuels.

One could argue that a D-^{3}He reactor would not use the tokamak configuration which is currently the workhorse of the D-T fusion research, and instead use an optimized magnetic configuration with higher β such as the FRC. This would reduce the requirements in confinement time and magnetic field to make the D-^{3}He scheme competitive. But then, D-T fusion would also benefit from a higher β, which directly affects the cost of electricity, so the comparison would not really be fair. In other words, any progress in the plasma physics allowing to improve the confinement would make the D-T fusion also more attractive, and paradoxically decrease the interest in D-^{3}He...

The spherical tokamak is, for example, the chosen configuration for the STEP project in the UK which aims to have a power producing reactor operating in the 2040s. A similar approach is pursued by the private company Tokamak Energy which aims to develop a high field spherical tokamak. Other approaches based on the tokamak aim to take advantage of the recent development of high temperature superconductors (HTS)[43] which in principle allow much higher magnetic fields than what is possible with the magnet type used for ITER, which uses conventional niobium-tin superconductors cooled at cryogenic temperature (3-4K)[44].

HTS offer the possibility to generate higher magnetic fields while decreasing the cooling requirements for the magnet system. This allows more compact tokamaks for a given output power to be designed. The bottom line is that maximization of β and B will allow both a faster development of D-T fusion and improve the feasibility of D-^{3}He[45].

Another important point to consider is that, at the temperatures required for D-^{3}He fusion, bremsstrahlung and synchrotron radiation will become important and will radiate significant fraction of the plasma power[37]. The plasma needs to be hot enough to not be limited by bremsstrahlung but not too hot that synchrotron radiation does not become too high. Such effects are not important in D-T fusion.

Energy conversion

Another advantage often mentioned for aneutronic fusion schemes is the possibility to use direct energy conversion to convert the energy of the plasma into electricity. For a D-T reactor, neutrons heat a fluid which is used to generate steam and produce electricity through turbines, as in thermal power plants (coal, nuclear)- see Box 3.

This limits the conversion efficiency to around 30-40%. As a matter of comparison, typical nuclear power plants have conversion efficiencies in the range of 35%[46] while advanced gas power plants with a combined cycle have efficiencies of up to 50-60%[47]. Advanced nuclear power plant concepts, using high temperature coolants and Brayton-type conversion schemes (a direct thermodynamic conversion cycle), promise efficiencies close to 50%[47].

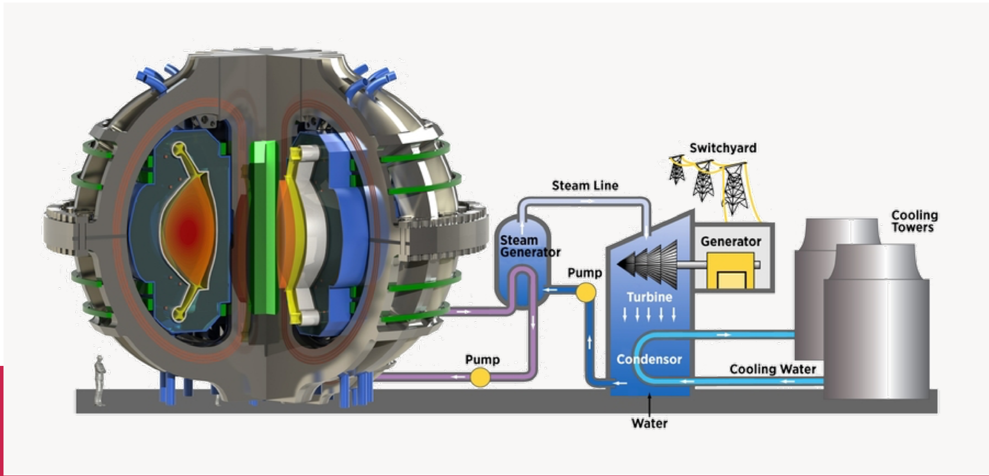
For aneutronic fusion the power is mainly carried by energetic particles except for the radiated power, which will be discussed in the next section. This is in principle well-suited to use the concept of direct conversion which aims at converting the kinetic energy of the plasma particles to electrical energy without going through thermal conversion[48].

Several concepts have been proposed in the literature[29] which all promise conversion efficiencies higher than 50% with up to 60-70% being mentioned[49].

Following the progress in advanced nuclear reactor designs, to raise the thermal conversion efficiency (up to 60% in the best case) in D-T reactors, they involve the use of higher temperature coolants[50] such as helium or liquid metals. While the first generation of fusion power plants will most likely not exhibit optimized efficiency and capacity factors[51], it is reasonable to expect that fusion reactors will tend to have higher efficiencies to become economically more attractive.

Direct energy conversion has not been demonstrated on a large scale yet and encompasses very significant technical challenges[52]. In parallel, thermal energy conversion is a well-known technique, and so it is difficult at this point to see whether it will be able to deliver on its promises.

In a magnetically confined plasma, the charged particles follow the magnetic field lines so that the contact between the edge of the confined plasma and the wall is highly localized. In a tokamak (this is also the case for stellarators), the plasma



Box 3

Power conversion

Many electricity-power plants are based on the principle of heating a fluid either by direct combustion (in the case of fossil fuels or biomass) or through neutrons in a nuclear reactor. The heated fluid generates vapor which is used to rotate a steam turbine which produces electricity. The diagram below shows how such a system would work for a D-T fusion reactor (Source). The thermodynamic efficiency of the conversion from heat to electricity is typically around 35%. The conversion is indirect because there is a step between the source of heat and the electricity.
The direct energy conversion is based on the idea of converting the energy of the plasma directly into electricity by using special structures and electric fields. The plasma particles would be slowed down, and as they do, they would create a direct electric current. This removes the intermediate step- hence the name.

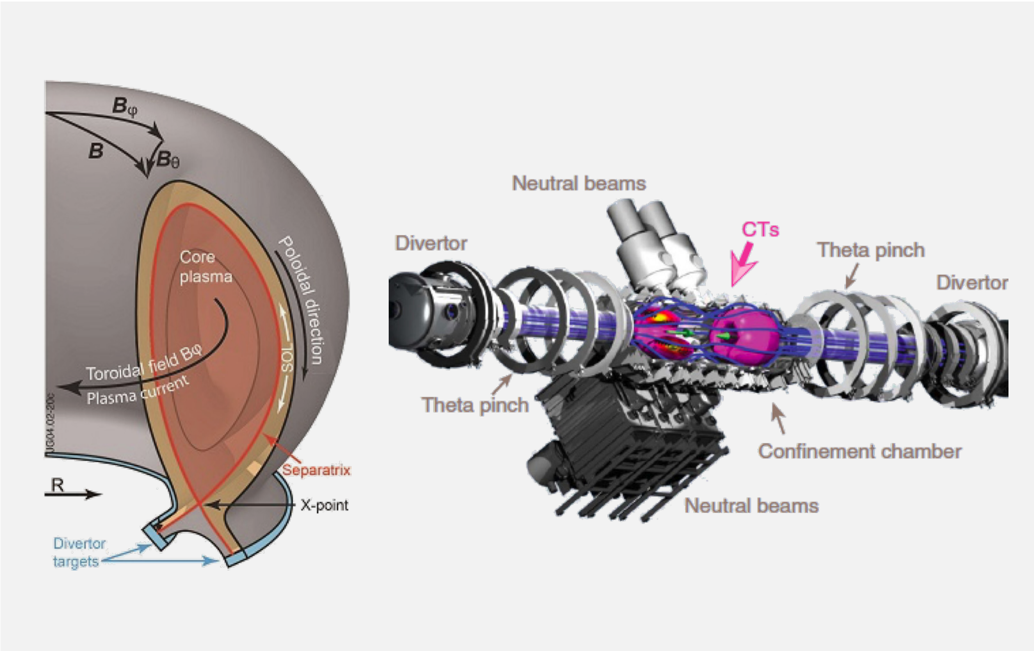


Figure 5: (left) Schematic representation of the magnetic geometry of the tokamak, illustrating how the plasma-wall interactions are concentrated at the bottom of the machine in the so-called divertor. (Right) Schematic principle of the Field Reversed Configuration studied for example by TAE. The plasma can exit at both ends of the machine.

power is mainly conducted towards a dedicated area of the machine called the divertor[53] (fig. 5). In ITER, the plasma deposition area in the divertor is about 3-4m^2 compared to a total wall area of about 800 m^2.

The unmitigated heat flux would be of the order of 40 $MW.m^{-2}$, much higher than can be handled by existing technologies (around 10$MW.m^{-2}$)[53]. Impurities (neon, nitrogen) are therefore introduced in the edge of the plasma to cool it down by radiating power away- the radiation is not confined to the magnetic field. If the entire fusion power is in the form of charged particles, as in the case of aneutronic fusion, the power handling becomes more difficult than in a tokamak.

In a DEMO reactor, more than 95% of the fusion power will need to be radiated away before the plasma interacts with the divertor so that the heat fluxes remain tolerable with material limits[54]. For an aneutronic scheme, this fraction will need to be higher than 99% which has never been achieved experimentally. Recent proposals for advanced divertor designs rely on modified magnetic structures to increase the flux expansion and the distance particles have to travel before getting to the divertor plates[55] which could in principle help in managing the heat flux challenge. This is at the expense of the engineering complexity since most designs rely on the integration of additional magnetic coils[56, 57].

At the temperatures required for D-^{3}He fusion, radiation emitted by charged particles will become important and will radiate a significant fraction of the plasma power[37], which will help in achieving high levels of radiation. This will increase the level of power deposition on the main chamber wall. The radiated power will, however, be deposited on the main wall and not only in the divertor, and will be collected through the cooling system. This will reduce the amount of charged particle power available for direct energy conversion and thus the overall efficiency. A tokamak device for D-^{3}He fusion would therefore need to combine thermodynamic and direct energy conversion.

This means that the fraction of the produced power which can be converted to electricity by direct energy conversion will be decreased accordingly, affecting the overall potential plant efficiency. An open configuration like the FRC (fig. 5) would be more appropriate for direct energy conversion because of the diverging magnetic fields at both ends, which facilitates the implementation of the required technology. At this stage the FRC concept is still far behind tokamaks in terms of performance (triple product) and there is little research on it.

Status of fusion research and prospects

D-T fusion

Unfortunately, mastering fusion for energy production has proven extremely difficult. Looking at the triple product, the progress made between the mid-1960s and the mid-1990s has been rather impressive (fig. 6) with a doubling time of the triple product every 18 months on average over that period. This has to be compared with Moore's law and the doubling of the number of transistors on a chip every 24 months. As shown in fig. 6, however, the rate of progress has fallen since the mid-1990s mainly because of the inertia of ITER and the lack of new large fusion devices between JET, currently the world's largest tokamak operating since 1983, and ITER.

The current planning for ITER foresees its

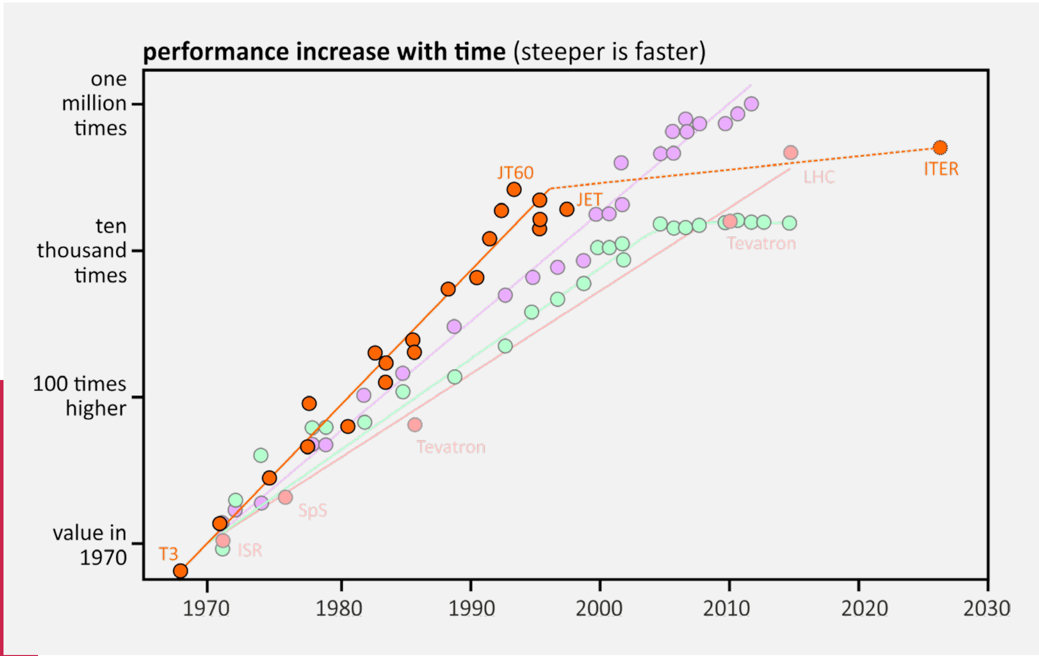


Figure 6. Comparison of the evolution of the figure of merit for performance for fusion, particle accelerators, and micro-processors.

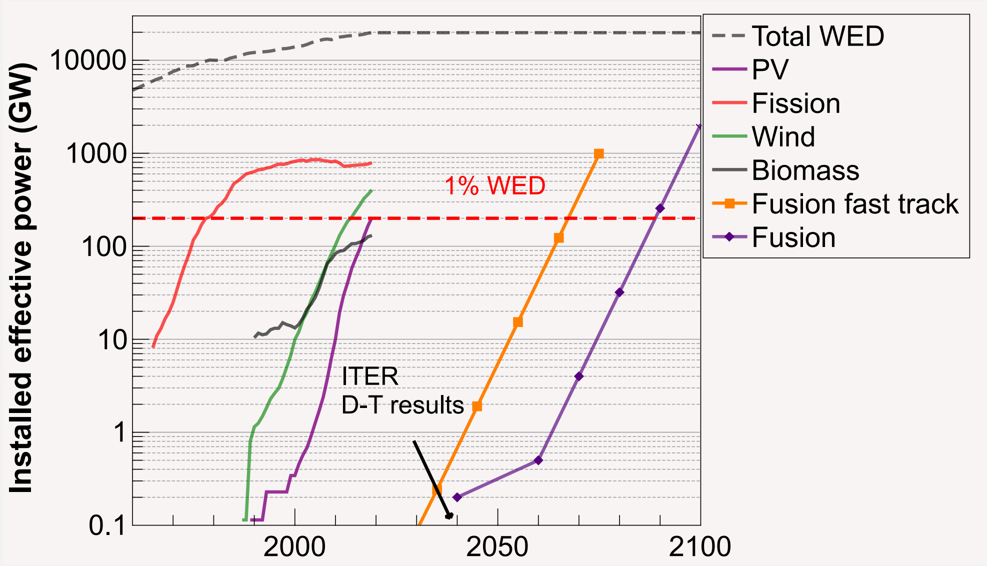


Figure 7: Comparison of the deployment rates for nuclear fission, wind and solar photovoltaic (PV) and expectations for the possible deployment rate of nuclear fusion under different scenarios. The red dotted line represents 1% of the World Energy Demand (WED)

first plasma around 2025 and the start of scientific exploitation around 2028[58].

The start of fusion operations and the achievement of the project's objective to demonstrate fusion energy will likely be in the late 2030s. The European roadmap for fusion aims at a demonstration reactor (DEMO) producing electricity in the 2050s[5]. Following that path, fig. 7 shows a possible deployment rate of fusion energy if one assumes the same type of deployment rates for fusion as for other energy technologies, with a doubling time of 2.5 years[2]. In such a scenario, fusion could produce a few percent of the world's energy demand towards the end of the century.

Several initiatives, some of them private, are trying to accelerate this timeline with a high-risk/high payoff approach taking advantage of recent technology developments such as high temperature superconductors, or 3D printing, and have a much more aggressive timeline. This is an encouraging sign that fusion development is now taken seriously and that there is a will to try and make fusion happen as soon as possible. If one of these initiatives could demonstrate fusion in the period 2025-2030, and following the same reasoning as above, fusion could represent 1% of the world's energy demand around 2060 and could play a more significant role in the second half of the century.

It should also be mentioned that, being a nuclear technology, fusion reactors will need to be licensed by the national nuclear authority- a process which so far has only happened for ITER in France[59]. This process will likely occur only when a given country considers building a fusion reactor[60], and needs to be taken into account when considering the deployment rate of fusion reactors- something which is rarely mentioned.

Social acceptance is currently a big issue The Nuclear Regulatory Commission in the US has recently initiated discussions on the definition of the regulatory framework for fusion reactors[61].

Where does D-^{3}He fusion fit in?

While the prospects for aneutronic fusion appear attractive when looking at the difficulties related to tritium breeding and neutron-induced material damage, moving away from the D-T fusion concept has several complications. First, the much higher plasma confinement and plasma pressure required to match the performances of D-T fusion have never been demonstrated experimentally. Admittedly, the focus of the worldwide fusion research has been on tokamaks and stellarators which have relatively moderate intrinsic β values.

Spherical tokamaks would allow operations with higher β but their low aspect ratio limits the maximum achievable magnetic field. While design studies show that a tokamak-based ^{3}He-fuelled reactor might be possible, it requires plasma performances far in excess of those reached in present devices[37,41]. More appropriate configurations for that fuel, such as FRC, are not as studied as tokamaks and considerable research would be needed to demonstrate the feasibility.

The development of materials resistant to neutron irradiation and concepts for tritium breeding are difficult challenges but they are topics of active research where

Admittedly, the focus of the worldwide fusion research has been on tokamaks and stellarators which have relatively moderate intrinsic β values.

innovation will likely permit progress within the next 30 years.

Similarly, because of the inherent complexity of fusion reactors, efforts are ongoing to maximize the potential energy conversion efficiency to go above those of current thermal power generation units. In addition, the heat produced in a fusion reactor could be used for different applications such as hydrogen production, similar to what is proposed for small modular nuclear reactors[62]. While direct energy conversion offers better conversion efficiencies on paper, it remains to be seen whether this would be a significant enough gain to compete with D-T fusion.

Because D-T fusion is 'much easier' to reach, it has had most of the attention and to date, very little, if any, research has been done on the D-^{3}He concept. The most advanced projects, ITER but also the most promising alternatives like stellarators, all rely on D-T fusion.

The much more demanding plasma performance and an absence of viable supply chain for ^{3}He make it a much more hypothetical technology, unlikely to see increased interest soon. The situation might change once an experimental demonstration of a gain higher than 1 has been made, be it by ITER or one of the private ventures, as fusion would then enter into the realm of feasible energy technologies and should see increased levels of funding.

Fusion is already known for having a reputation of not delivering on its promises[7] and thus concepts with lower probability to succeed are unlikely to be funded at this point.

For all those reasons, D-^{3}He fusion would only become a potential technology for a second or third generation of fusion reactors, the development of which would only really start when D-T fusion reactors get deployed in mass.

There are therefore several conditions which need to happen if D-^{3}He is to

The development of materials resistant to neutron irradiation and concepts for tritium breeding are difficult challenges

become a reality, including:

- D-T fusion proves successful and is used in mass
- The level of waste produced by D-T fusion becomes socially unacceptable
- Suitable technologies exist for massive recovery of 3He from the Moon
- The price of resource import from the Moon becomes competitive with those of terrestrial resources
- Depleted resources in Li or Be

Those conditions are unlikely to be met before at least the end of the 21st century. It is of course not possible to predict how things will develop in later centuries to come, but if D-T fusion is mastered it would provide a very attractive source of energy with abundant resources. Would humanity benefit from the use of another scheme in the distant future? Perhaps, but at present the case is certainly not very strong considering the technical challenges it encompasses.

It is rather paradoxical that ^{3}He is so often mentioned when it comes to space, while it receives so little interest now in fusion research. While new papers come out episodically about it[63,64], the main focus remains on developing and deploying fusion reactors based on deuterium and tritium. It is likely to remain the case for decades to come…

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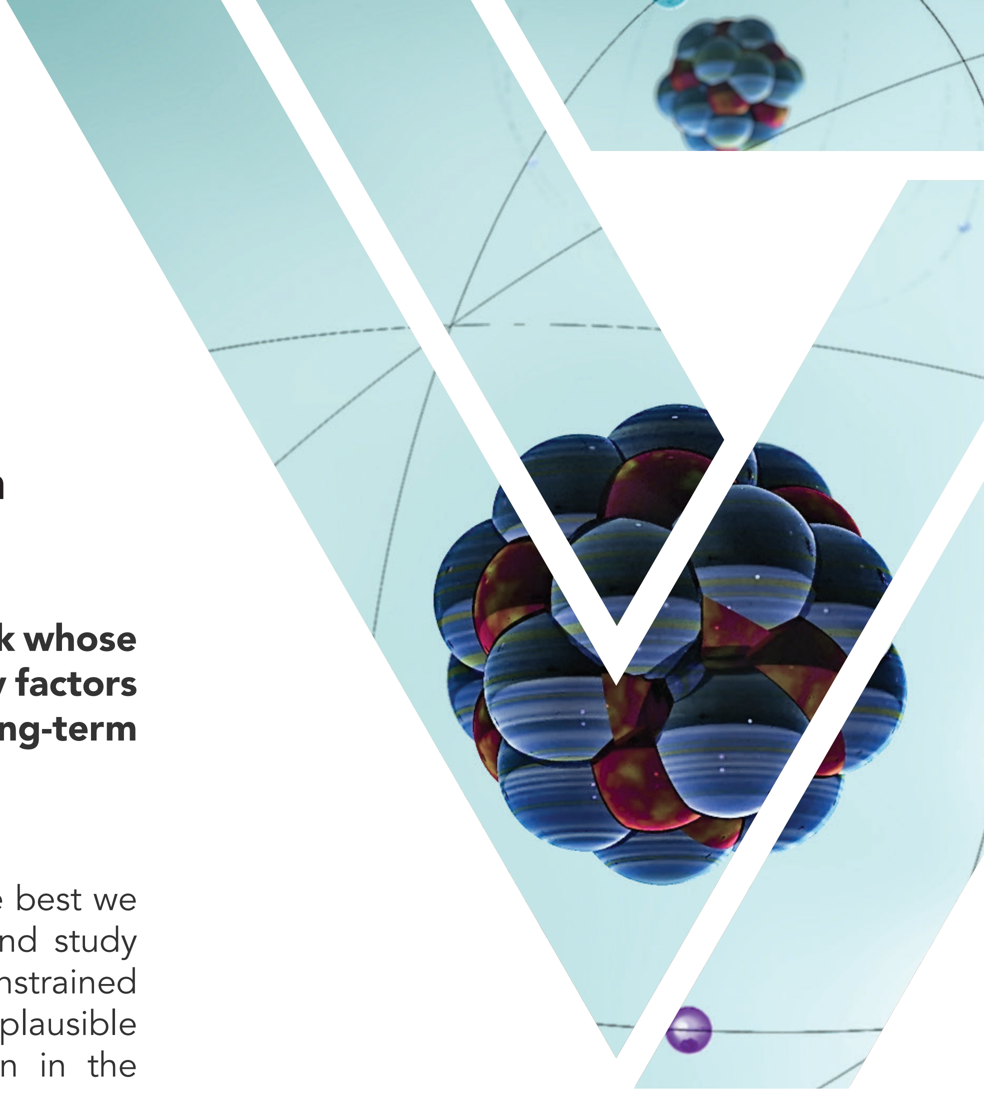

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