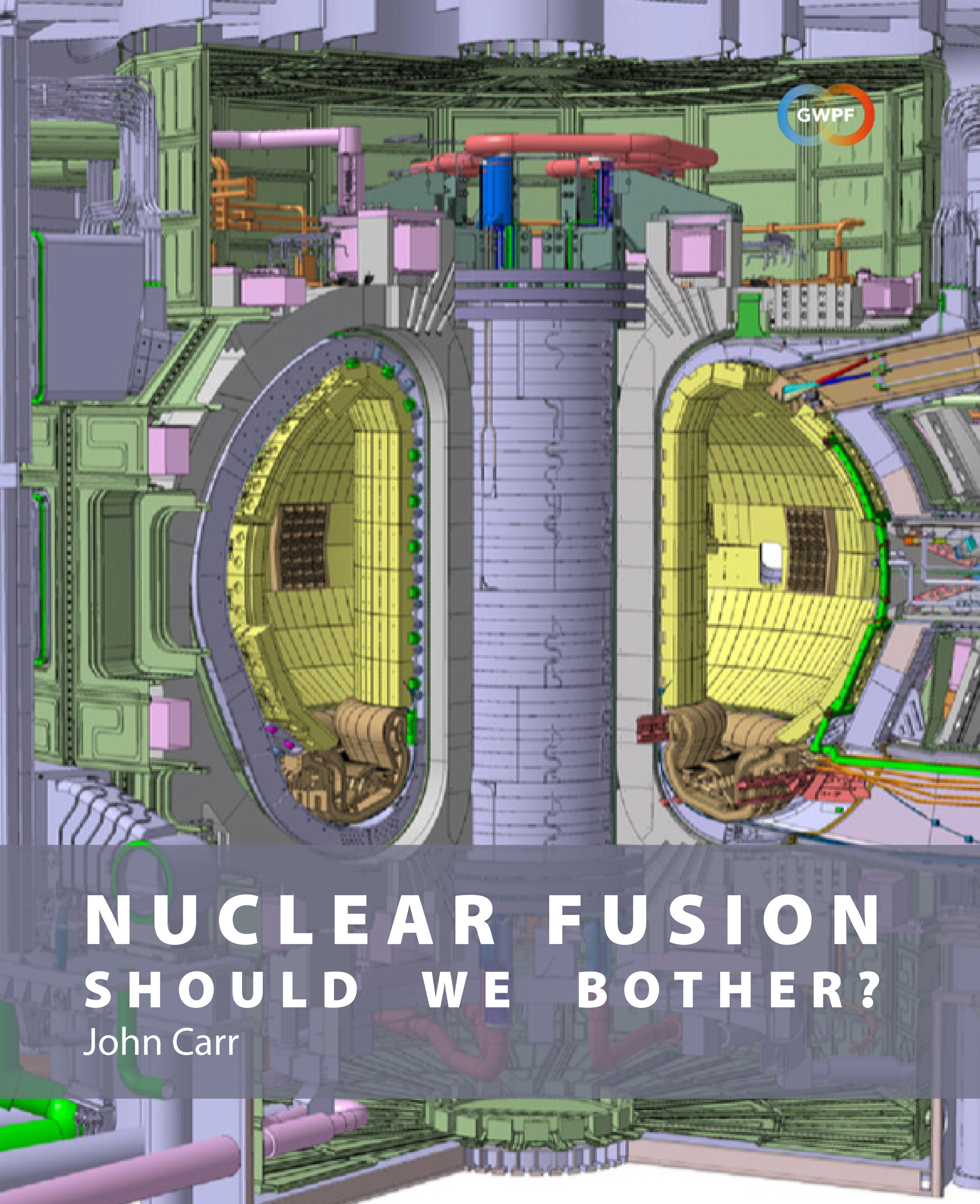


NUCLEAR FUSION

SHOULD WE BOTHER?

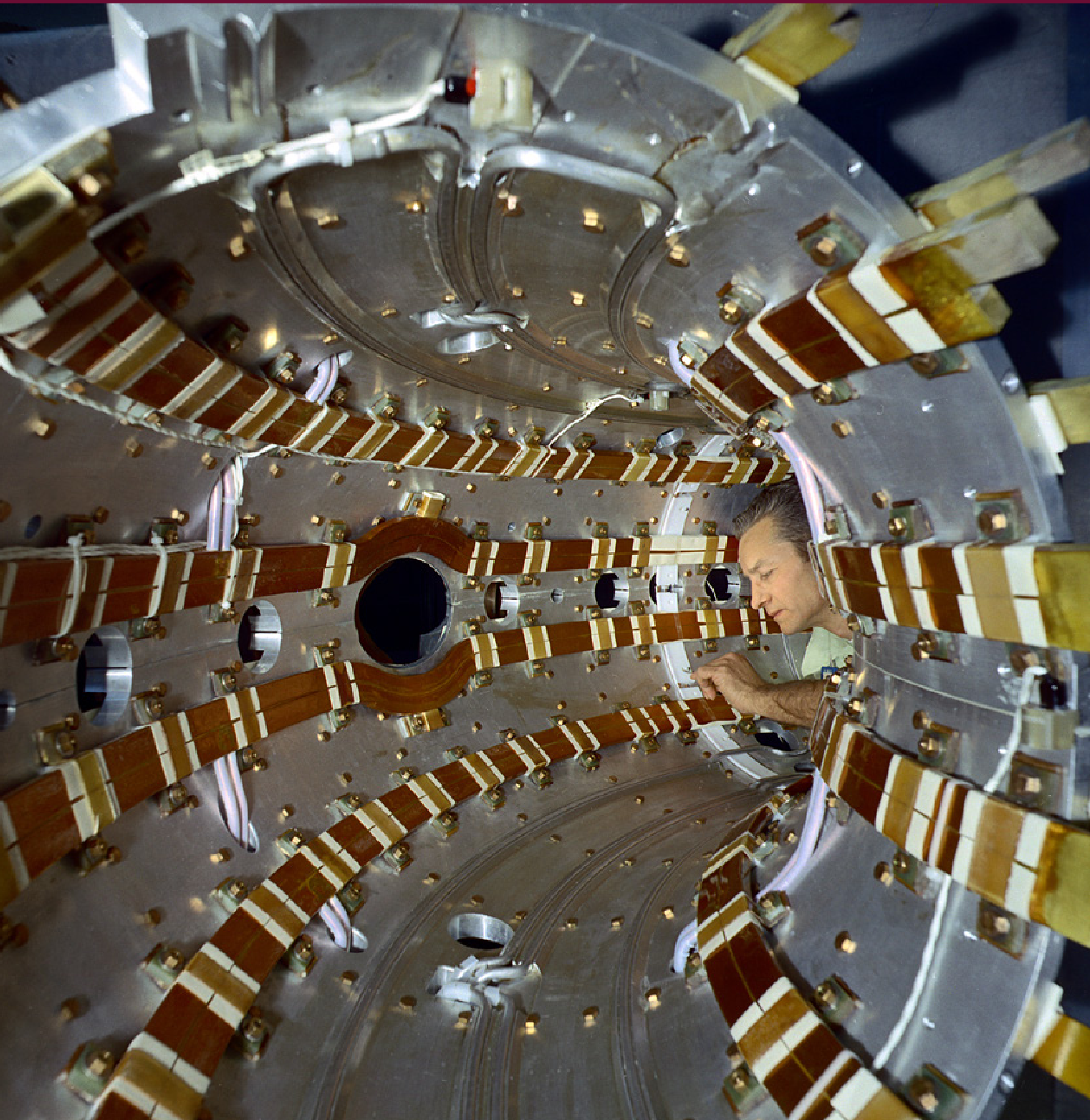
John Carr

The Global Warming Policy Foundation
Briefing 66

Nuclear Fusion: Should we bother?

John Carr

Briefing 66, The Global Warming Policy Foundation



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About the author

The author is a retired research scientist. He obtained a PhD in high-energy nuclear physics at Imperial College, London in 1974, and then embarked on an academic research career in particle physics and astroparticle physics research, at several institutions around the world, culminating in the position of Director of Research at the CNRS in Marseille, France from 1990-2016. Since retirement, he has studied a number of issues related to climate change and has recorded his findings on the website: Climate Change and Electricity Generation (www.climate-and-hope.net).

Acknowledgement

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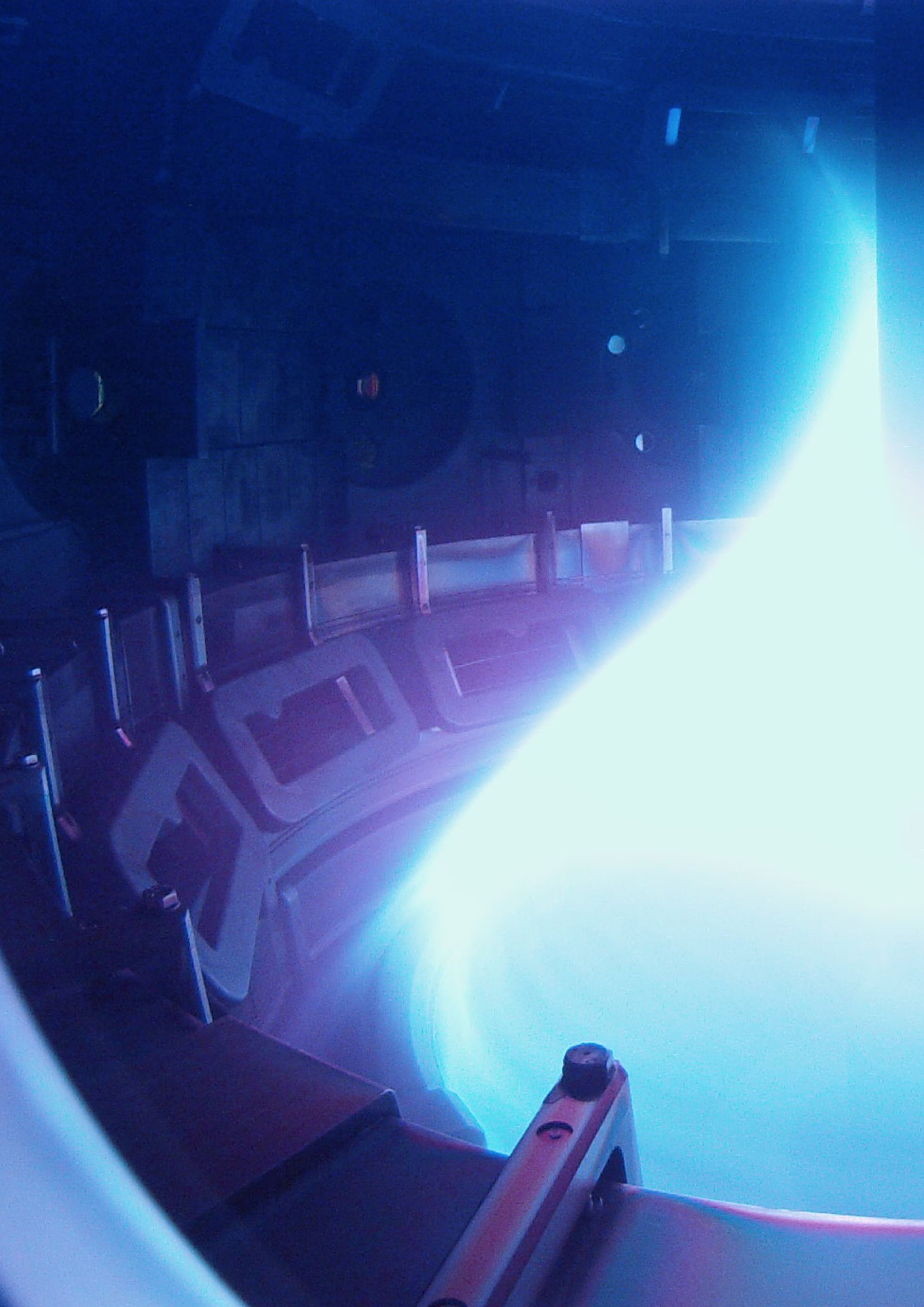
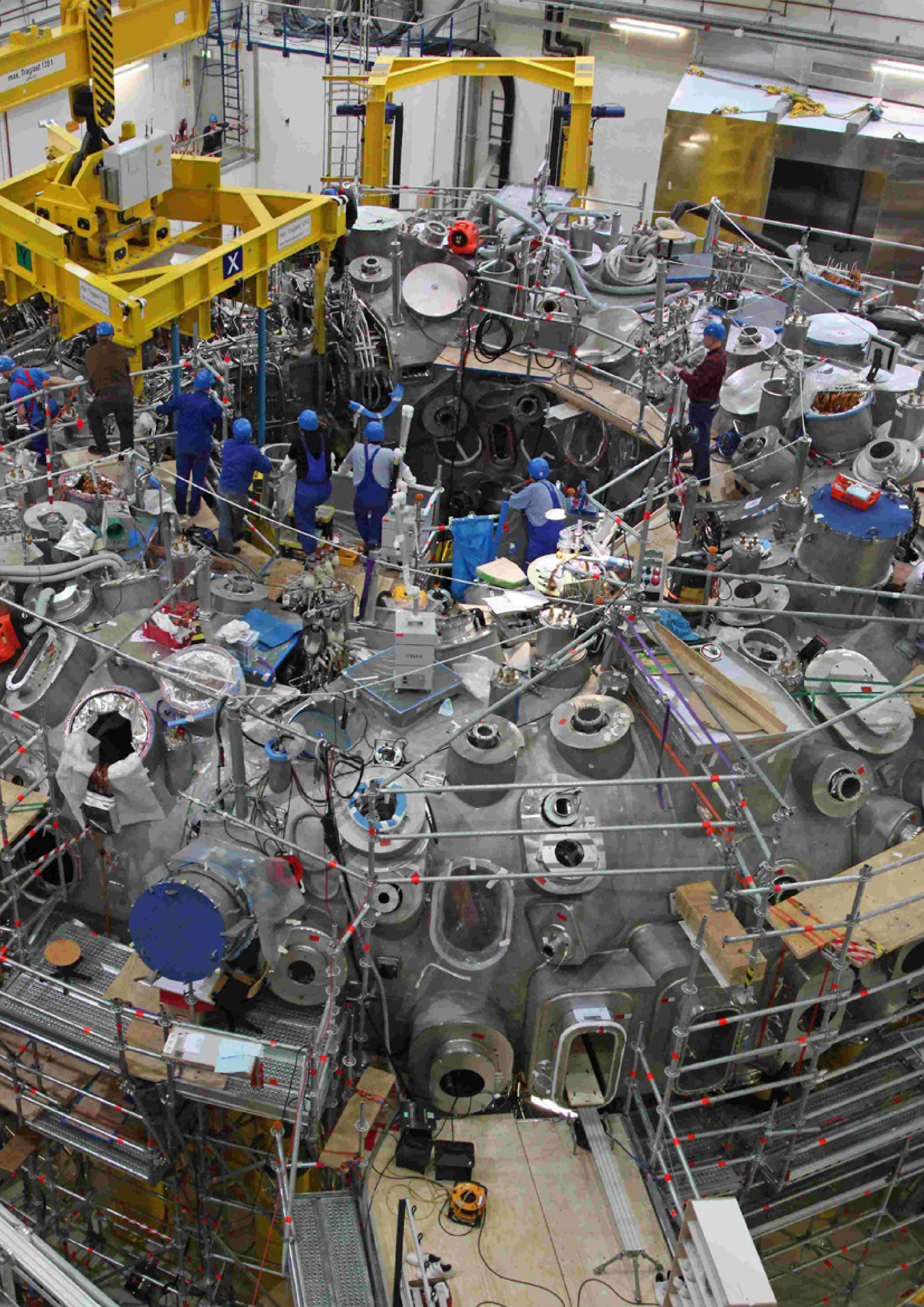


Executive summary

- Nuclear fusion is the energy source of the sun, but after more than 70 years of research effort it has never been harnessed to produce electricity on Earth.
- Research has converged on a favoured type of fusion reactor, the Tokamak, of which more than 200 have been built worldwide.
- A power plant based on this mainstream tokamak technology will inevitably be very costly and unable to compete economically with the already functioning nuclear fission power plants.
- Sales pitches to obtain funding for continued fusion research tend to positively compare fusion with fission, making statements which range from disingenuous to false.
- The mainstream approach to fusion has a litany of technical difficulties, from degradation of materials due to radiation damage, to lack of tritium fuel supply.
- The latest international experimental tokamak, ITER, has suffered many delays and engineering problems, which must cast doubt on its future success.
- In the past couple of decades, numerous private startup companies have appeared, with a great variety of ideas to improve on the mainstream fusion approach.
- The coming decade will see either great progress for fusion power or great disappointment, but at best there will not be a significant amount of electricity from commercial fusion for several decades into the future.
- Given the recent renaissance in nuclear fission it is unlikely that fusion will ever serve a purpose in the electricity market.
- Fusion has no relevance for reductions of climate-changing carbon dioxide emissions, simply because of the likely timescales for deployment.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1. Introduction

Nuclear fusion is the energy source of the whole Universe, since it is the origin of power in the Sun and all active stars. The quest to harness this power to produce electricity on Earth has been underway for nearly a hundred years, but thus far, no electricity has ever been generated from fusion.

Nuclear fusion – using isotopes of hydrogen – has followed a very different path to nuclear fission – using isotopes of uranium – to make power. While the physics behind both technologies was developed in the 1930s, fission is now producing around 10% of the world's electricity, while fusion is producing none. Figure 1 compares the nuclear physics of fusion and fission energy generation. In fission, following the absorption of a neutron, a uranium nucleus splits into two lighter nuclei, releasing about 200 mega electron volts (MeV) of energy, as well as neutrons with energies of around 2 MeV, which can interact with other uranium nuclei, triggering them to fission in a chain reaction. In fusion, nuclei of the two heavy hydrogen isotopes, deuterium and tritium, combine to form a helium nucleus, producing an exploitable energy of 14 MeV, carried by an emerging neutron.

There are several different technologies for producing fusion energy on Earth, but by far the most widely adopted is the tokamak, which has been used for the Joint European Torus (JET) at Culham, UK, and is also the technology of the International Thermonuclear Experimental Reactor (ITER) prototype currently under construction in France, as well as for the subsequent DEMO demonstration fusion power plant. Both ITER and DEMO will be covered in detail later in this paper.

I will focus mainly on tokamak technology, often referred to as 'mainstream fusion', and only at the end will discuss alternatives. The opinions expressed here are condensed from my website,[1] which contains many more technical explanations, as well as a glossary defining most of the technical terms used.[2]

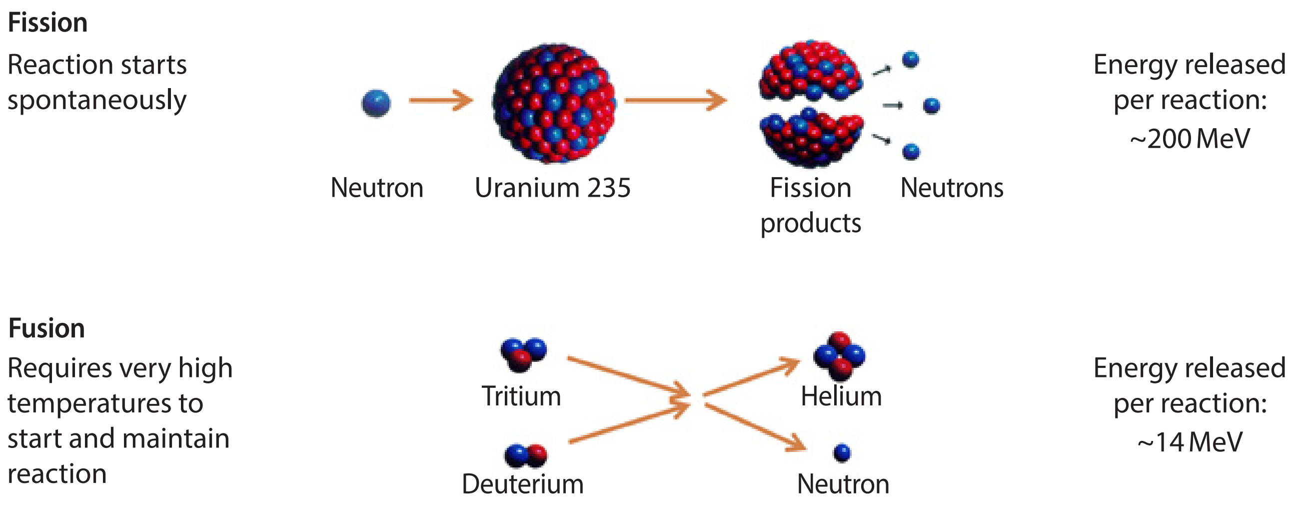


Figure 1: Nuclear fission and nuclear fusion reactions.

In fission, a uranium nucleus splits into lighter isotopes releasing an exploitable energy of about 200 MeV while for fusion, the two nuclei of deuterium and tritium combine to form a helium nucleus, producing an exploitable energy of 14 MeV.

2. Fusion versus fission

Any rational evaluation of the wisdom of pursuing fusion as a commercial power source must compare its prospects with the reality of commercial fission generation.

The first nuclear fission reactor to be connected to an electricity grid was at Calder Hall in the UK in 1956. Fission power expanded rapidly on electricity grids around the world until the 1980s, when it stalled due to economic and safety concerns. However, in the past few years, it has become clear that fission will soon rapidly expand again, largely because it is seen as the optimal economic solution, delivering large-scale weather-independent low-carbon electricity.

Fission is therefore now commercially well established, and fusion businesses must necessarily compete with it. Table 1 compares the main parameters of fission and fusion for power generation. These are expanded upon in the text and are justified in detail in the references. We shall see, however, that strategies for the development of fusion power often entail implicit and explicit criticisms of fission.

Table 1: Main parameter comparison of fission and fusion

	Fission	Fusion
Operating temperature	Less than 1000°C	Over 200 million °C
Fuel type	Solid	Plasma
Energy density	>100 times higher by reactor volume	3 times higher by atomic mass
Availability/reliability	>85%	30% ?
Cost (relative per MWh)	1	>10
Fuel availability	Uranium abundant	Tritium scarce
Radioactive waste	Partly long-lived	Mostly short-lived
Safety	Historic accidents	Many complex systems with risks

Energy density (Table 1, line 3) is frequently discussed in a very misleading way when comparisons are made between different electricity generation technologies, such as coal, oil, gas, fission and fusion, with an oft-stated conclusion that fusion uses the fuel with the highest energy density. For example, taking the nuclear reactions in Figure 1, it is said that while fission produces 200 MeV for an atomic mass of 235 units, fusion produces 14 MeV for a sum of atomic masses of only 5 units, so that fusion yield must be higher by mass energy density.

However, if the environments of the nuclear physics and the volumes involved are considered, the situation is very different. Fusion takes place in a low-density ionised gas (plasma) at temperatures over 200 million degrees Centigrade, while fission takes place in a solid, with a much higher mass density, at temperatures of less than a thousand degrees. A typical nuclear fission power plant produces 1000 MW of electricity from a reactor core with a volume of around 50 m^3, while the DEMO fusion power plant is being designed to produce 500 MW in a tokamak vacuum vessel with a volume of around 5000 m^3. Fission therefore has a 200-fold advantage in *volume energy density*, which will have a considerable impact on the costs of the civil engineering involved. A fusion plant will therefore inevitably be much more expensive than a fission plant of the same power capacity.

The next widely misrepresented measure of fusion is availability/reliability: the fraction of the time the plant produces electricity, also referred to as the capacity factor (CF). The CF for fission is normally higher than any other electricity generation technology. Fusion will have a low CF for two separate reasons: scheduled maintenance stops and breakdowns. Certain tokamak components will need to be replaced every few years due to the radiation damage caused by the impacts of high energy 14 MeV neutrons. High breakdown rates will be inevitable, due to the multiple complex systems necessary for plasma control and heat extraction, as discussed later.

CF directly affects the price of electricity in the fusion/fission comparison: it is expected that the cost of fusion-generated energy will be nearly a factor three higher per megawatt hour than for fission-generated electricity due to CF alone. This major disadvantage of fusion-generated electricity is discussed elsewhere,[1,3] but does not alone give the full story.

Ultimately – of course – cost will drive all decisions about commercial fusion. Unfortunately, since no official estimate of the costs of the DEMO power station has been published, any figures that exist can only be treated as speculation. It is sometimes claimed that fusion would a have similar unit cost to fission power, but this is clearly not the case due to the enormous physical size and complexity of fusion power plants. The factor of more than 10 in Table 1 includes estimates of extra costs of the complex systems needed for fusion power plants, which are not necessary in fission plants.[1]

A simpler estimate can be made by comparing the actual build cost of ITER, taking its theoretical potential for electricity production – even though in reality, by design choice, it will produce none – with the expected cost of a new nuclear fission reactor. The latest generation of European reactors, such as the one at Flamanville in France, entering operation in early 2024, cost around €13 billion each for an electricity generation capacity of 1650 MW. Learning from this experience, EDF (Electricité de France) will build a series of EPR2 reactors from 2024, starting at Penly, with a cost of €8.6 billion for similar capacity. The cost of ITER is given as €50 billion,[4] and, based on its designed thermal power, it has the hypothetical potential to produce around 200 MW of electricity. This means that it would deliver eight times less power than an EPR2 reactor for six times higher cost; in other words a factor 48 higher build cost per megawatt of output power.

Fuel availability is also claimed – disingenuously – to be an advantage for fusion reactors. Deuterium-tritium (D-T) fuel is by far the simplest fuel for fusion since it requires the lowest temperature (still 200 million degrees Centigrade) to initiate the nuclear reaction. Some new fusion projects propose alternative fuels, but the increased difficulties involved with these are rarely mentioned.

For mainstream projects, using D-T fuel, the difficulties in obtaining tritium are also glossed over. Due to its rapid radioactive decay, only tiny amounts of tritium exist in nature, so fusion projects plan to regenerate it within the power plant itself. The physics for doing so has been studied for decades, but as yet there has been no practical demonstration of a working tritium breeder system. Even if tritium regeneration does eventually work, it will be difficult to provide a start-up stock for each new fusion power plant. At present, all commercial supplies of tritium come from a specific type of fission reactor, the Canadian designed CANDU, which uses heavy-water neutron moderation, and currently has a tritium production rate of about 0.5 kg/year. A single fusion power plant would require at least 2 kg to commence operations and it is probable that the best way to fuel future new fusion power plants will be to operate a set of such fission reactors to supply the start-up tritium.[1,3]

The nature of radioactive waste in fission and fusion is different but is an issue for both. For fission, the problematic waste comes from the spent fuel rods, which contain fission products and unused uranium: this is high-level waste, with a long radioactive lifetime. In fusion there is no spent fuel waste – since the reaction product is stable helium, and the unused tritium is recycled – but there is a large amount of intermediate-level waste created by neutron activation. Neutron activation and radiation damage is a more serious problem in fusion than in fission, because of the higher-energy neutrons emitted.

There is a great deal of confusion about this issue. Some projects, described later, intend to use alternative fuels, with no neutron emissions, and thus would avoid this problem. However, the vast majority of fusion projects use D-T fuel and do have major radiation activation and damage issues. For example, the 'breeder blanket' modules, which have the twin function of extracting the power (as heat) from the reactions and regenerating tritium, will become radiation damaged, and will have to be replaced every few years (using complicated remote handling machines).[1] Moreover, the underground repositories used for storing high-level fission waste are unsuitable for the much larger volumes of the intermediate-level waste from fusion reactors, and the only plans to deal with this issue are – so far – enormous structures on the fusion power plant sites themselves.[1]

Fusion reactors raise several safety concerns, including the possibilities of radioactive leaks and hydrogen explosions. Advocates often point out that fusion reactors have no risk of core meltdowns of the kind that happened at Chernobyl. However, it must be noted that the Chernobyl reactors were of a very old (1960s) Soviet design, with a known tendency to instability.[5] Modern fission reactor designs raise no such concerns. It is perhaps best to say that both fusion and fission have risks that must be managed, and it is not possible to claim that one system is intrinsically safer than the other.[1]

3. Tokamak fusion technology

From the 1950s to the 1970s, research and development programs around the world advanced a multitude of different techniques for nuclear fusion, but by the 1980s most efforts had started to focus on tokamaks, and magnetic plasma confinement. The description given here illustrates the complexity of the numerous systems needed to build a functioning tokamak, which are completely absent in fission reactors. An understanding of this difference should make clear why fusion is so much more costly than fission, and also why it will be a much less reliable power source.

In tokamaks, a low-pressure plasma is confined in a vacuum vessel by a complex system of magnetic fields. Plasma is the fourth state of matter, where the atoms are broken apart into their nuclei (or ions) and the electrons. Both are contained in the magnetic fields, but it is the nuclei which fuse to produce energy. Figure 2 schematically illustrates the magnetic fields and plasma circulation in a tokamak.

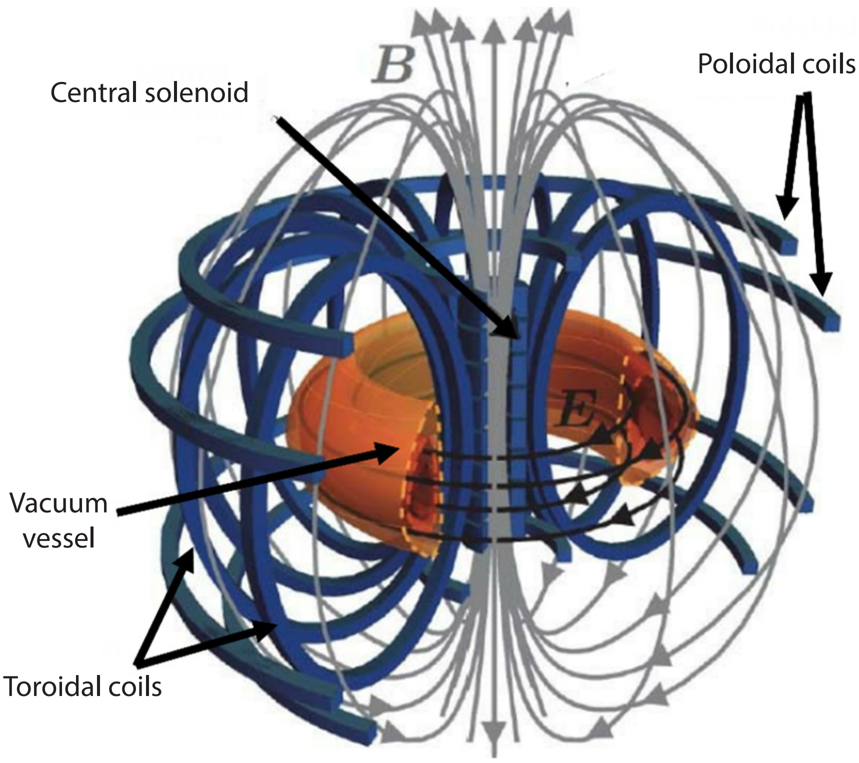


Figure 2: Magnetic confinement configuration in a tokamak.

Two sets of coils, toroidal and poloidal, generate magnetic fields in different directions to confine the plasma. In addition, the central solenoid produces a vertical, variable, magnetic field which induces an electric field and current in the plasma, producing ohmic heating. (Credit: Justin Ball).

Figure 3: Cross-section through a tokamak.

Central axis out, showing schematically the major components. The plasma is depicted in pink, breeder blanket in red, vacuum vessel in yellow and various magnetic field coils in blue.[15]

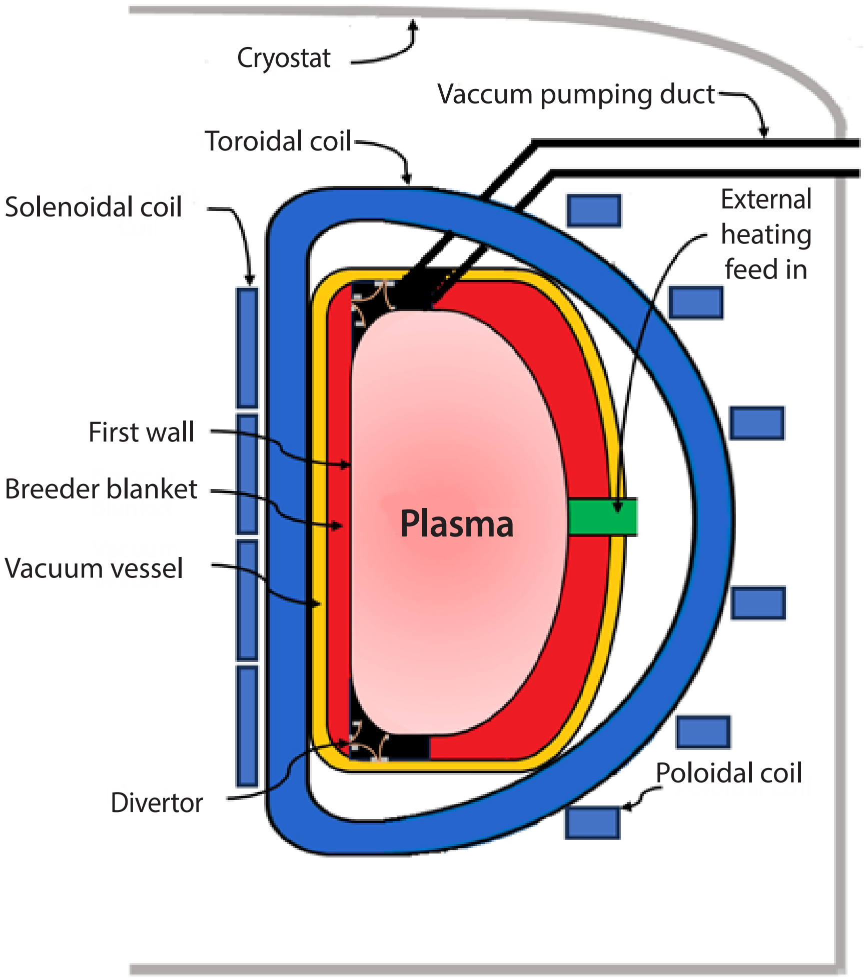


Figure 3 shows the major components in a tokamak:

- superconducting magnets – toroidal; poloidal and solenoidal (also shown in Figure 2);
- cryostat and liquid helium cooling of the magnetic coils – to maintain their superconductivity;
- breeder blanket – for the breeding of tritium and extraction of heat from plasma;
- divertor – to exhaust the plasma at the end of confinement period;
- external heating systems – for heating the plasma to initiate fusion.

These have no equivalents in fission power plants, and so add greatly to the relative cost. The superconducting magnets, associated power supplies, and cooling systems are projected to be less than half the cost of a fusion power plant.

The sequence of operations in a tokamak starts with the injection of a few grams of deuterium and tritium gases, the atoms of which are stripped of electrons to become a plasma. This enters the vacuum vessel, and the changing solenoidal magnetic field causes it to circulate around the torus. Collisions within the plasma cause some heating, but additional heating must be supplied by external systems to attain the extremely high temperature – 200 million degrees Centigrade – needed to initiate the fusion reactions. When the fusion reactions are active, the energy is radiated out of the plasma by the 14 MeV neutrons, which pass through the 'first wall' and into the 'breeder blanket', which, as noted above, has the dual function of extracting heat and producing new tritium.

Such tritium production is essential for the operation of a fusion power plant due to its scarcity in nature. The ideas to do this involve a variety of nuclear reactions, usually in two stages, as shown in the example of Figure 4. Several other possibilities for the nuclear reactions exist, using different elements, along with various options for the physical configuration of the breeder blanket.

After a certain time, the confinement cycle in the tokamak is ended and the plasma is exhausted from the vacuum vessel. This takes place in the 'divertor', a very challenging part of the tokamak due to the intense heat and radiation levels it must endure. The higher the power of the reactor, the shorter the survival time of the divertor, because of radiation damage. It is planned to replace the divertor every two years in the future DEMO plant, in a complex remote-handling operation expected to last four months. This will cause significant downtime and consequently lower machine availability.

Once extracted, the highly radioactive breeder blanket modules and divertor cassettes must be stored for decades in an 'active maintenance facility', which again adds significantly to the operational costs.

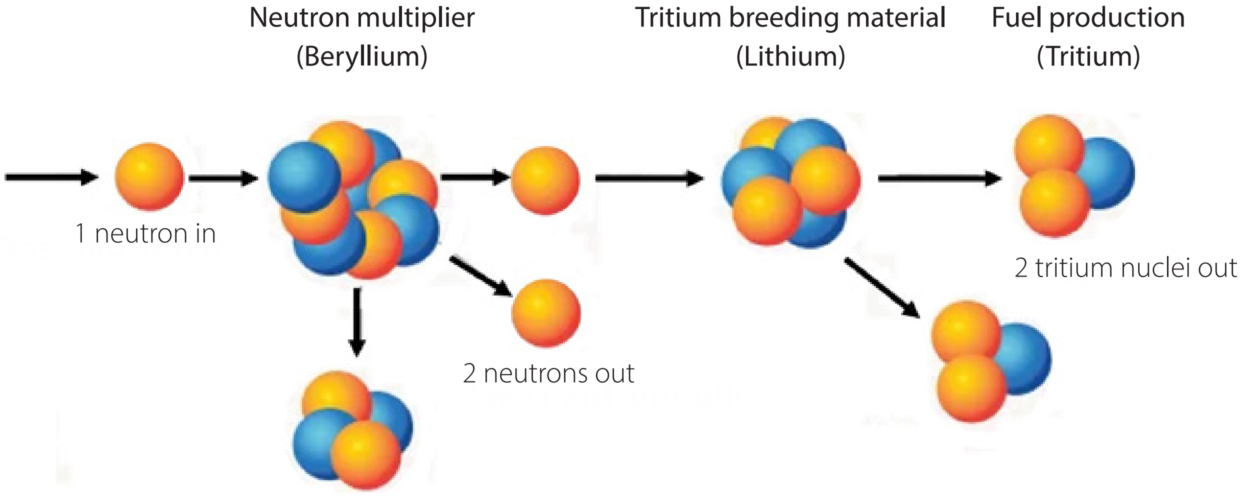


Figure 4: Example of a possible tritium regeneration reaction sequence.

In the breeder blanket material, the beryllium reaction multiplies the neutrons and the lithium reaction generates the tritium..

4. ITER and its status

To date, more than 200 tokamaks have been constructed, with 54 still operational around the world. The ITER project is the largest to date, with a plasma volume 10 times larger than JET, the previous record holder, which operated in the UK from 1983 to 2023. Only two tokamaks have so far actually produced fusion: JET in 1991, and the American TFTR reactor in 1993/1994. ITER has the objective of being the third, advancing knowledge of plasma physics in the process. It will develop technologies required to deliver a commercial power plant, but it will not go as far as to produce electricity itself.

The ITER project began in 1985, following a Reagan/Gorbachev initiative, and currently has seven members: China, the European Union, India, Japan, Russia, South Korea and the USA. Figure 5 shows a computer art view of ITER, with the cryostat vessel in grey, and the internal components (the vacuum vessel illustrated in yellow).

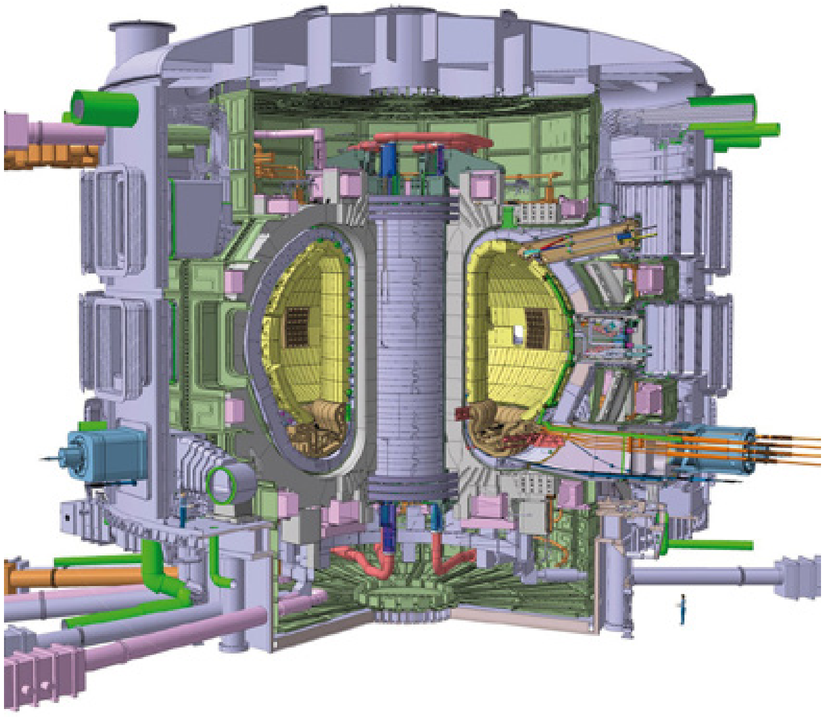


Figure 5: ITER tokamak design with cryostat and interior components.

The cryostat (grey) has a volume of 16,000 m^3, diameter of nearly 30 m and height of 30 m. Credit: ITER.[16]

Construction on the ITER site started in 2010. Figure 6 shows a view of the tokamak building in September 2023.

Until 2021, construction was advancing according to a schedule published in 2016, in which the tokamak would be complete and the first experiments (called 'First Plasma') conducted in 2025, with the 'Nuclear Phase' (with the first fusion experiments) scheduled to start in 2035. Unfortunately, during 2020, the first in a series of problems became apparent. In August 2020 the initial vacuum vessel sector, shown in Figure 7(a) – one of nine required to complete the toroidal vacuum vessel – was delivered to the ITER site, despite having already been found – at the manufacturer's facility – to have

Figure 6: The ITER site in September 2023, showing the tokamak building.

The Tokamak Building and the Tokamak Assembly Hall are the tallest structures at the centre of the image. All the other structures are ancillary buildings. There is also a very large (400 MW) electricity feed-in power complex. Credit: ITER.[16]

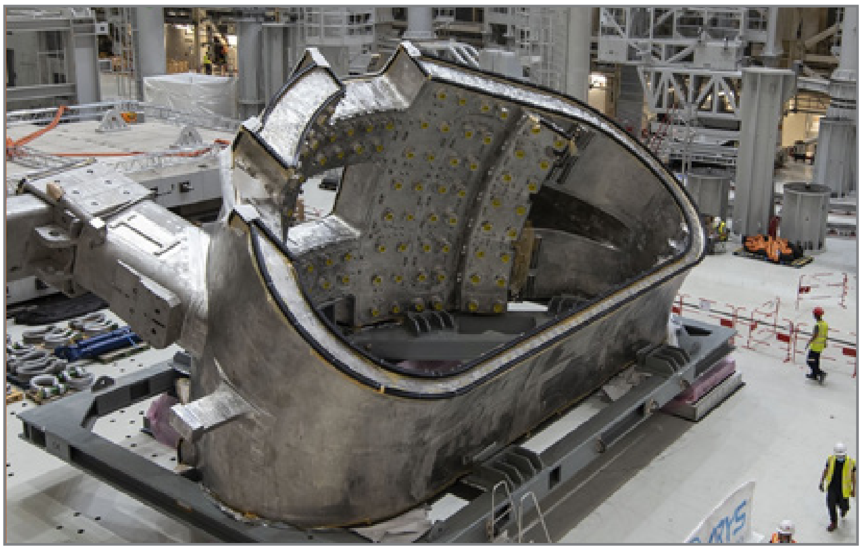
dimensional non-conformities. It was nonetheless accepted by ITER. These non-conformities – also found in other sectors – were one of the reasons that the French nuclear regulating agency, the Autorité de Sûreté Nucléaire (ASN), issued a letter on 22 January 2022, in which it refused to release a 'hold point' on the assembly of the ITER tokamak. This has effectively stalled any irreversible assembly operations (including inter-sector weld assembly) of the facility since that date. Reversible assembly operations were allowed to continue, however, and in May 2022 the sub-assembly comprising vacuum vessel sector #6 together with its thermal shield and two toroidal coils, weighing 1250 tons, was lifted into the tokamak cryostat housing, allowing valuable experience to be gained in the manipulation of such large structures.

The ASN letter raised questions in four areas pertinent to ITER safety, namely:

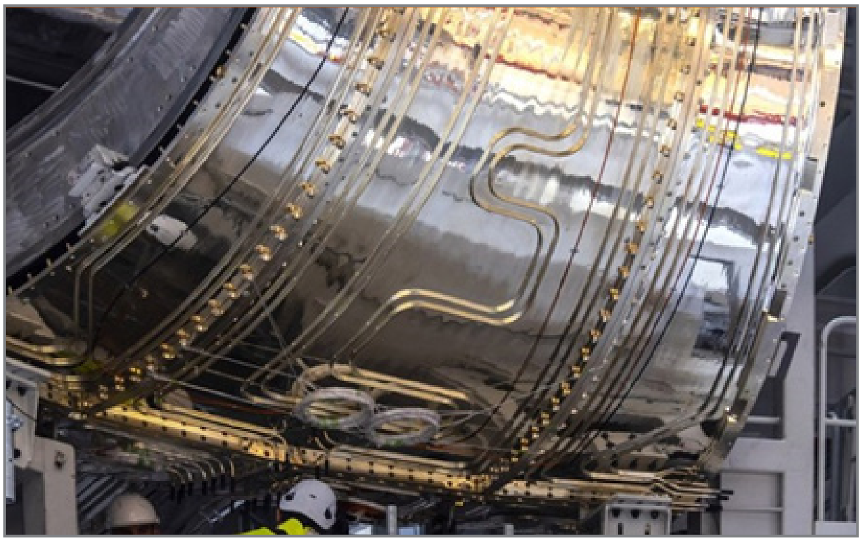
- the welding strategy required to overcome geometrical non-conformities of the welding bevels of the delivered vacuum vessel sectors;
- assessment of fission products due to uranium impurities in beryllium;
- clarification of radiological maps and dimensioning of biological (radiation) shielding around the tokamak;
- demonstration of civil engineering structural behaviour under extreme conditions.

Figure 7: Problem ITER components.

(a) Vacuum vessel sector #6 (12 m high, 7 m wide, weighing 440 tons), which was found to have dimensional non-conformities.
(b) Thermal shields, which fit outside the vacuum vessel sectors, have leaks in their piping. Credit ITER.[16]



(a) Vacuum vessel sector



(b) Thermal shield

Point 1 relates to the vacuum vessel sector defects. Three years after the problem was discovered, a solution does not seem to have been decided upon.

Point 2 refers to uranium impurities in commercial beryllium metal, which, under neutron irradiation in the fusion reactor, would undergo fission. For reasons related to plasma physics, it had initially been decided that the first wall – the surface closest to the plasma – would be built from beryllium. The impurity fission problem, and the fact that beryllium is also very toxic, led to a decision to use as little beryllium as possible in ITER. Instead, it has been decided to use tungsten in the first wall from the beginning of the programme. Beryllium is still being considered, however, as a material in the breeder blankets (Figure 4).

Points 3 & 4 are still under discussion.

All of the critiques raised in the ASN letter must be fully addressed before ITER construction can advance unimpeded.

During tokamak assembly operations, a further major problem was found in the thermal shields, one segment of which is shown in Figure 7(b). These fit outside the vacuum vessel sectors to intercept and remove significant heat that would otherwise arrive at the superconducting toroidal coils, which must operate at cryogenic temperatures (–270°C), attained using liquid helium cooling. In November 2021 testing of the cooling pipes – intended to circulate cold helium gas in the thermal shields – revealed leaks. After a detailed study, it was decided in November 2022 that some 23 km of the thermal shield piping would need to be replaced.

An additional technical problem was found in 2022. This related to bolts in the gravity supports of the toroidal field coils. It was discovered that one of them had sheared only 40 days after installation; that is, before any application of additional operating stress from magnet field forces. The cause was a metallurgical defect. This problem, coming after all the others, raises the question of whether there are other issues still to be discovered, and whether there has been adequate quality control in the project.

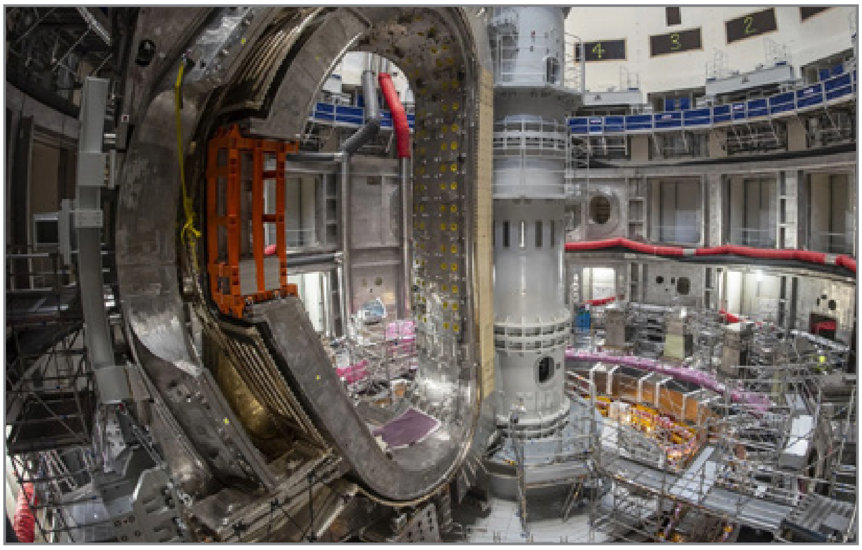
ITER is, in some sense, lucky, in that all these problems have been found before the completion of the tokamak assembly: after that milestone, disassembly and repair would be essentially impossible.

Two in-situ views of the ITER tokamak assembly status, taken roughly 18 months apart, are shown in Figure 8. In the top image (May 2022), the first of the nine tokamak sectors had been lifted into place inside the cryostat housing. In the lower one (November 2023), this sector had been removed for disassembly and repair.

At present, the consequences of these problems are limited to delays and cost overruns. Final decisions on procedures, the schedule and project finance will not be made until 2024.[6] Until then, the project is operating without an agreed overall plan, and only estimates of the delays due to the current problems can be made. One estimate is that the first plasma experiments will take place between 2030 and 2035, a delay of 5–10 years relative to the 2016 Baseline Schedule.[4]

Figure 8: Evolution of the ITER tokamak assembly.

In early 2022, assembly was in full swing, but by late 2023 disassembly was evident, with progress apparently in reverse. Credit ITER.[16]



(a) May 2022

(b) November 2023

5. Towards a fusion power plant

ITER will be a prototype fusion reactor and will never produce electricity. So, to obtain commercial fusion power there needs to be further research and development. ITER's main purpose is only to advance knowledge of plasma physics, and the fusion reactions involved will not run for long periods. As a result, it will be of little help in developing the engineering necessary for a commercial fusion power plant, and in particular the structures able to survive the intense neutron radiation of the fusion reactions, as well as complete breeder and tritium purification systems.

While ITER is run as a multi-national collaboration, the future will see many different parallel development projects around the World. The final step before commercial fusion will be a demonstration power plant, often referred to as 'DEMO'. Figure 9 schematically shows a DEMO tokamak plant sending superheated water to a heat exchanger which feeds a steam turbine to produce electricity.

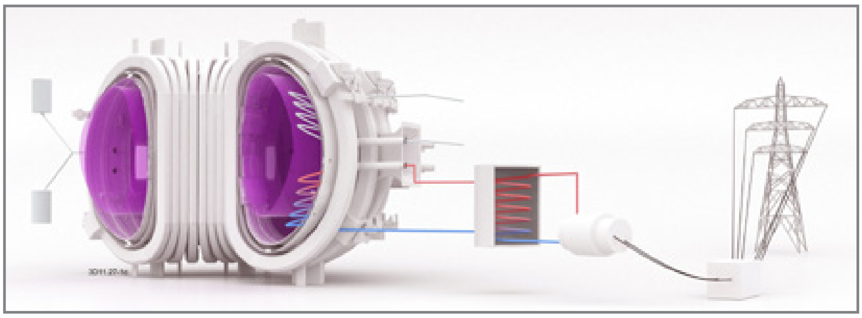


Figure 9: Schematic of a demonstration fusion power plant, DEMO, to follow on from ITER.
Credit: EUROfusion.[17]

There has, however, been controversy on the development sequence towards a DEMO plant, particularly in the area of material radiation resistance studies. Two different development paths are shown in Figure 10.

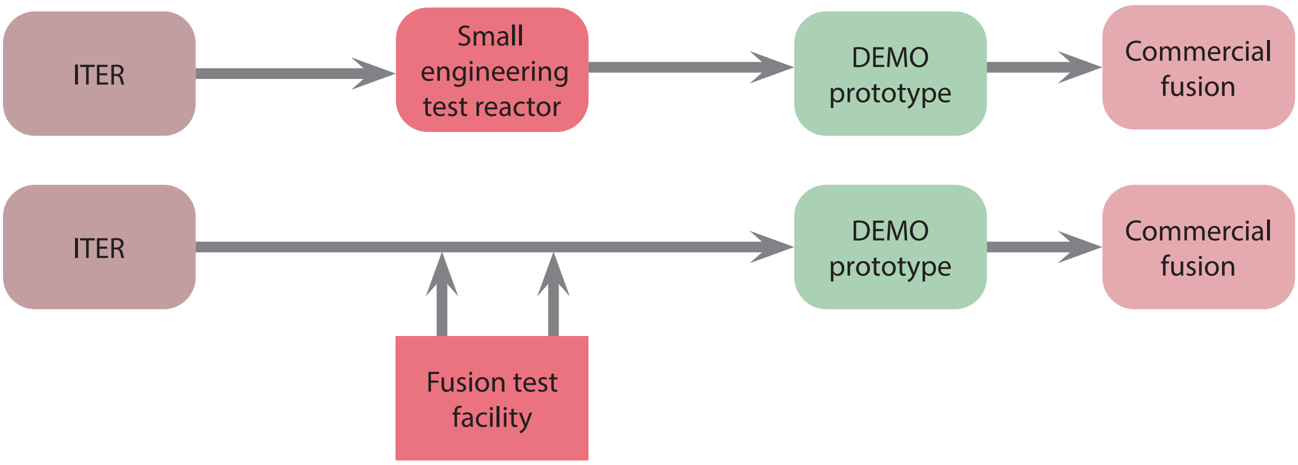


Figure 10: Alternative development paths towards mainstream commercial fusion power plants.
Top: preceding DEMO, a stage with a small engineering test reactor is favoured in the USA, China and India. Bottom: input to the DEMO design from a fusion test facility; a scheme favoured in the EU, South Korea and Japan.

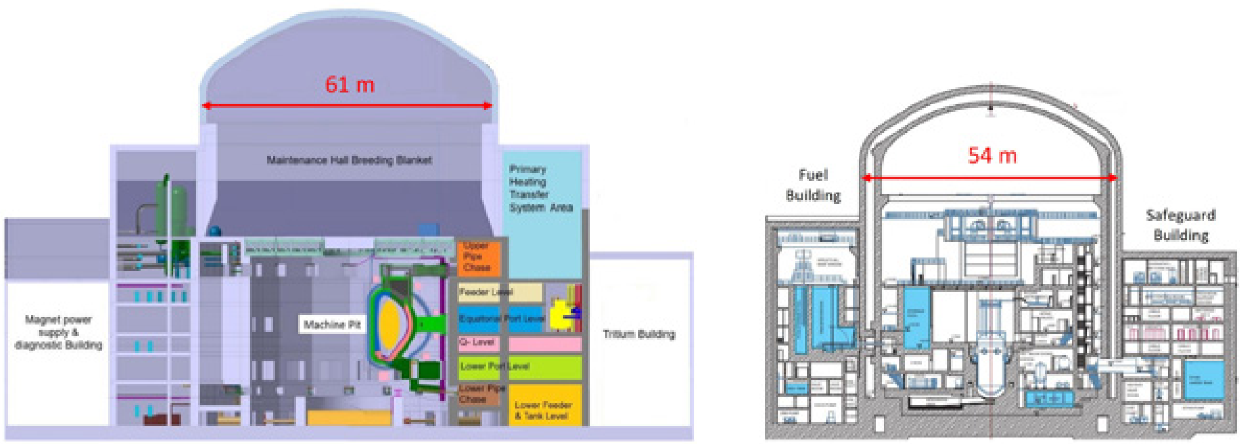
In the USA, there has been - for a long time - a movement to build a small test fusion reactor on which to develop the engineering required. In the ITER organisation, there have been plans for the International Fusion Materials Irradiation Facility (IFMIF),[7] which will be a test facility in which candidate materials for use in an energy producing fusion reactor can be fully examined. IFMIF is an accelerator-based neutron source that produces, using deuterium-lithium nuclear reactions, a large neutron flux with a spectrum similar to that expected at the first wall of a fusion reactor.

These facilities would both be used to develop materials and breeder blankets before construction of the full-blown DEMO fusion power plant. Given the importance of these issues, and despite decades of theoretical studies, it is amazing that no significant practical experiments on this path have been performed – due to the paucity of funding for a suitable test facility.

Work on the design of DEMO has already been in progress for several years – without the benefit of a test facility. It is based on ITER, scaled up 1.5 times in linear dimension and with a plasma volume about three times greater, in a tokamak with a radius of 9 meters. The plasma retention time is designed to be 2 hours, compared to 10 minutes for ITER, with the objective to have an electricity output from the plant of 500 MW.

To continue in the spirit of the fusion-versus-fission comparison, Figure 11 shows views of a fusion power plant and a conventional fission power plant.

While the containment structure housing the tokamak of a fusion plant will be similar to that of the fission plant containing a reactor, the scale and number of auxiliary buildings to house the extra complex systems of a fusion plant will be much greater. Indeed some buildings, such as the Active Maintenance Facility, are not even shown in this illustration. For emphasis, again, the



(a) Fusion (b) Fission

Figure 11: Comparing the physical size of a fusion power plant and a fission power plant.

(a) EU 500-MW fusion plant design for DEMO and (b) the 1650-MW EPR2 fission plant to be built first at Penly, France starting in 2024. Although the physical size of the fission plant is smaller than the fusion plan, it will provide three times as much electricity and be operational at least 25 years earlier.

major complex systems needed for a fusion power plant absent from a fission power plant are:

- cryoplant to supply enormous volumes of liquid helium for cooling;
- tritium breeder blanket systems with tritium separation and purification plant;
- complex remote handling equipment to extract highly radioactive components for replacement;
- active maintenance facility, needed to handle, store, and recycle the used breeder blanket modules and divertor cassettes.

The EU-DEMO planning is naturally linked to future experience from the operation of ITER. In the 2018 EUROfusion Roadmap document, DEMO commissioning was scheduled to start in 2051. Clearly, any ITER delays will impact this date, so it now seems unlikely EU-DEMO could operate before 2060.

6. Alternatives to mainstream fusion

The story related here so far is of the dismal progress towards a product that has zero advantage over operational fission power, will be of pharaonic size and entirely uneconomic.

Many people have now arrived at this conclusion, and a large number of new fusion projects have been launched, aiming to do better. Figure 12 shows the number of fusion devices in development around the world. By far the largest number are tokamaks, but there are many other experimental projects focused on alternative concepts, either in operation or at the planning stage.

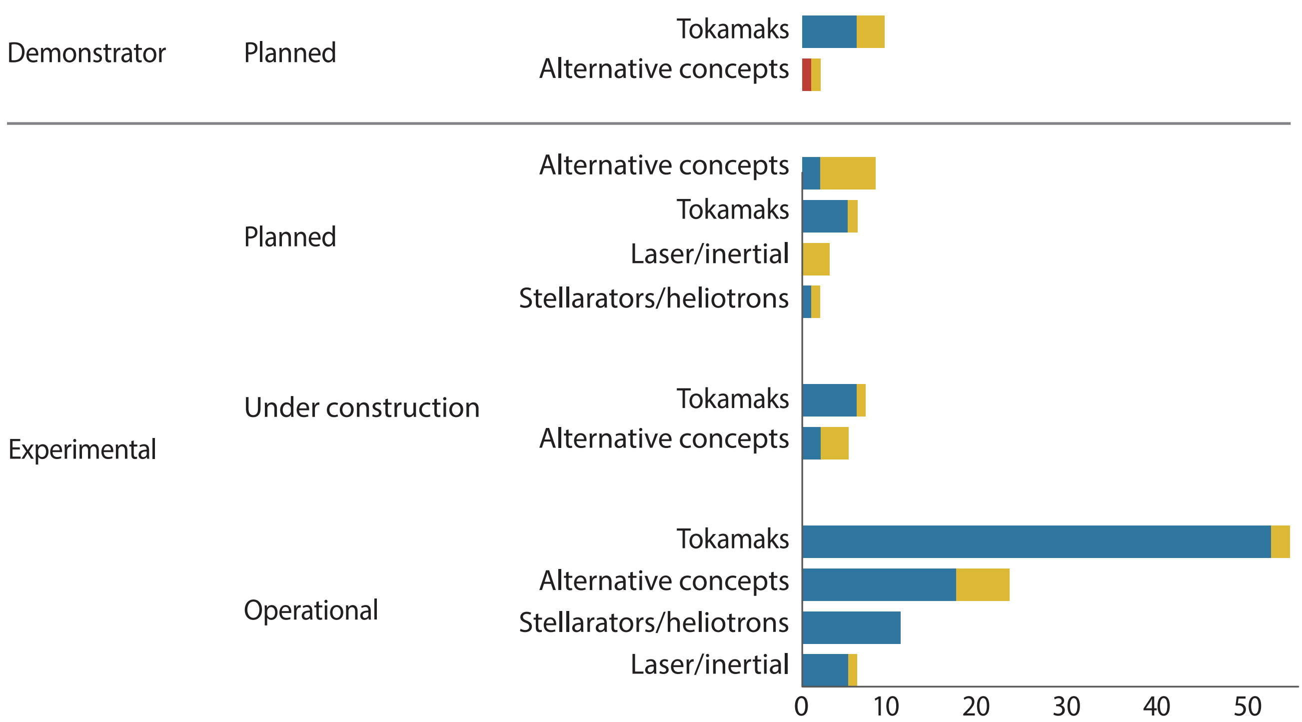


Figure 12: Number, type and status of world fusion devices.

Blue, public; orange, private; red, public/private. From IAEA survey 2022.[18]

Many of the projects in the 'alternative concept' class are privately funded. The growth in this field started in 1998, and by 2023 there were a total of 43 major companies involved, of which 24 had declared funding of more than $10 million.[8] Figure 13 illustrates the growth of the private fusion sector. The majority of these companies (15/24) are pursuing alternative concepts, while some (9/24) are building toroidal magnetic confinement devices, such as compact tokamaks, which are variants on the mainstream approach. A few of the companies (5/24) are proposing the use of alternative fuels. Many were founded by frustrated academic researchers, and all obviously want to avoid the pitfalls of mainstream fusion.

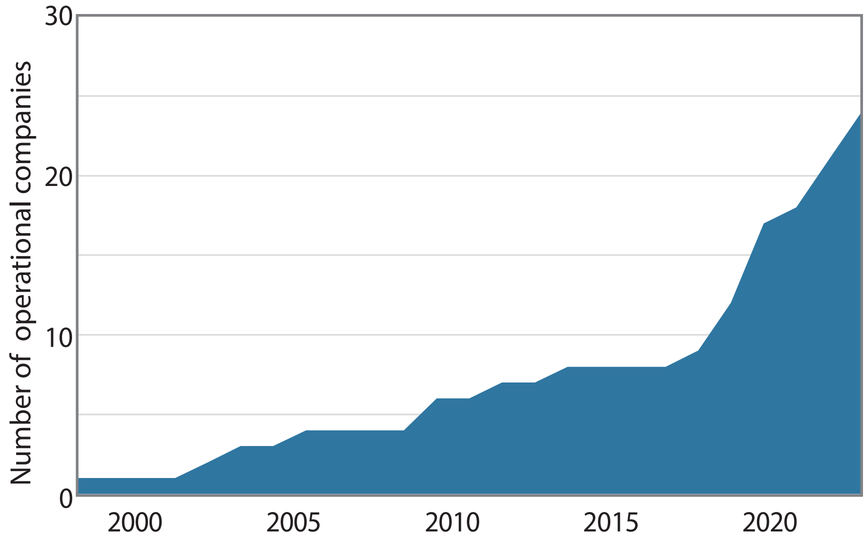


Figure 13: Genesis of the private fusion companies.

The plot shows the growth in the number of companies each having received an accumulated funding >$10 million. The two largest companies are Commonwealth Fusion Systems, started in 2018, which now has investment funding of more than $2 billion and TAE Technologies, started in 1998, with funding of over $1.2 billion.

The two biggest private companies can be used to illustrate the very different approaches being taken.

TAE Technologies[9] was one of the first private fusion companies, and at present has the second largest investment budget. It has adopted an approach of doing everything differently from mainstream fusion, starting with the fuel. TAE is studying the use of proton-Boron (p-B^{11}) to replace D-T, because Boron is both abundant and the reaction produces no neutrons.

While this gives TAE the enormous publicity advantage of there being no radioactivity in their power plant technology – in contrast to most of the other private projects, as well of course as fission – the snag is that this fuel requires six times the reaction temperature of D-T (> 1 billion degrees). Critically, the radiation losses in the plasma are higher, to the point where an energy gain is impossible, according to calculations.[10] It is surprising that this company, which has prospered for 25 years, is advocating a technology that many experts say can never work.

The Commonwealth Fusion Systems (CFS),[11] 'Affordable, Robust, Compact' (ARC) tokamak design,[12] has a very different approach, following a strategy of fixing what is broken with mainstream fusion and not trying to sell the use of seemingly impossible alternative fuels and technologies. The conceivably fixable difficulties with mainstream fusion are the enormous construction cost and the low availability issue. The innovation of CFS is to use high-temperature superconductors (HTS), in the form of the new rare-earth barium copper oxide (REBCO) material, rather than the usual superconductor of niobium-tin and niobium-titanium used in ITER. Using HTS allows ARC to use higher magnetic fields and thus be smaller.

The ARC design is therefore half the physical size of ITER for a similar fusion power output. As already emphasised, the enormous physical size of ITER/DEMO is a major reason for its huge cost, so a change in the tokamak volume by a factor of eight could change the situation significantly. CFS gives a rough construction cost estimate for ARC at about \$6 billion, compared with ITER's \$60 billion. The use of HTS brings another considerable advantage: the possibility of dynamic joints in the magnet coils, allowing the tokamak to be split in two for maintenance and repairs. ITER/DEMO, once completed, cannot be realistically disassembled for major repairs.

Regrettably, these performance enhancements of ARC come with technical challenges to overcome. The REBCO superconductor is brittle – being a ceramic rather than a metal. In addition, the use of higher magnetic fields results in greater mechanical stresses, so constructing reliable magnets is more difficult. Further, the smaller size means the same fusion power output must be extracted through smaller breeder blanket systems and divertors, requiring these devices to sustain higher temperatures and radiation doses – another major challenge.

A number of other private fusion projects are developing fusion devices similar to ARC, some with different magnetic storage configurations; the new fusion project of United Kingdom Atomic Energy Authority, the Spherical Tokamak for Energy Production (STEP),[13] is one example. However, all depend on REBCO superconductors, and so face similar challenges to ARC.

7. Conclusion

The arrival of the private fusion companies, making claims for commercial fusion power stations to be connected to the electricity grid in the early 2030s, has the potential to dramatically change the prospects for the technology. This commercial optimism will compete with technological reality during the next 10 years; the oldest private fusion companies, including TAE, have already passed the original dates for which they promised commercial fusion.[14] Such claims must therefore be taken with a pinch of salt. In parallel with these private company claims, ITER will have to readjust to a new schedule for fusion reactions after 2035. So, should these private companies succeed, it will be difficult to see why the ITER/DEMO programme would continue.

This article has emphasised intrinsic concerns for commercial fusion, the major points being:

- excessive cost compared to fission, because of enormous size and complexity;
- low operational availability due to the necessity to frequently replace components damaged by neutron irradiation;
- scarcity of tritium fuel, requiring regeneration in operations and probably supplies for startup from a fleet of fission reactors.

Some private companies have possible remedies for the first two points, through use of high temperature superconductors. However, these solutions raise new challenges and it is highly likely that the timescales to develop the new technologies will be very much longer than the commercial promises.

The answer to the question in the title of this paper, therefore, is that there is no reason to bother with fusion. It will almost certainly have no advantages over fission and will come – at best – a hundred years later than the Calder Hall milestone, costing vastly more. The timescale for fusion is such that it has no relevance for the reduction of climate-changing carbon dioxide emissions.

Notes

1. John Carr website: Nuclear Fusion https://www.climate-and-hope.net/electricity-technologies/.c/nuclear-fusion.
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6. ITER Council Press release, 17 Nov 2023: IC-30 Press release.
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18. World Survey of Fusion Devices, https://www.iaea.org/publications/15253/world-survey-of-fusion-devices-2022.

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