BUILDING A STAR ON EARTH:

promising progress on the path to clean and plentiful energy from nuclear fusion

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What problem do you most hope scientists will solve in the coming years? Prof Stephen Hawking, when asked this question, said nuclear fusion[1]. Scientists, politicians, and even dictators[2], have long sought the 'holy grail' of energy production – to replicate how the Sun produces energy here on Earth. In recent years, astonishing progress in our understanding of just how to do that has been made.

Nuclear fusion is the cousin of nuclear fission, but where fission involves the splitting of heavy atoms, such as Uranium, fusion is the combining of light atoms, such as hydrogen, into heavier atoms. The new heavier atoms are just a fraction lighter than their constituent parts were, with the difference in mass being released as energy according to physics' most famous equation, $E = mc^2$. It is this process that powers all stars in the Universe and, indirectly, most life on Earth.

Why should we pour resources into replicating this process on Earth? The goal, it must be said, is not just to fuse two atoms – that has been done many times – but to produce a net gain in energy from fusion reactions; an entirely new power source. Given that much of what makes life pleasant in the modern world is reliant on the consumption of energy, and that the advantages of fusion energy are hard to underestimate, this is an important goal.

David MacKay, Chief Scientific Adviser to the Department of Energy and Climate Change, estimates that the supply of fuel for the most simple fusion reaction would last a world population of 6 billion for more than a million years[3]. Not only is there a supply well beyond the fossil fuel horizon of 100-150 years[4], but the fuel for fusion is found in seawater, meaning that energy security would never again be an issue. This would solve two serious geopolitical problems; that of countries using their fossil fuels to achieve political objectives, and that of terrorist organisations who have captured fossil fuels exploiting them to fund their activities, a situation most recently and tragically demonstrated by the rise of ISIS[5].

Construction of the US National Ignition Facility.

The greatest problems with fossil fuels, which currently account for 87% of world primary energy consumption, are their negative externalities. The most widely known is global warming due to gases released by the burning of fossil fuels. The 2013 Inter-governmental Panel on Climate Change report is clear, and uses what is, for scientists, very strong language [6]:

"It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century."

Climate change is certainly happening, and its effects are causing suffering now. The World Health Organisation estimates that around 120,000 deaths worldwide were caused by climate change in 2004 [7]. Fusion produces no CO_2 and its main by-product, Helium, is in short supply. Fossil fuels also produce air pollution, which was linked to more than 28,000 deaths in the UK in 2010 according to Public Health England [8] with a significant proportion coming from energy generation [9]. Surprisingly, Westminster, and Kensington and Chelsea, have the joint highest number of attributable deaths due to air pollution of anywhere in Great Britain. Fusion produces no air pollution.

The word nuclear often unfairly prompts concerns over safety. Today's fission power plants give an insight into how safe a fusion plant would be. Fission has a reputation for being dangerous, but several reputable studies have concluded that it is far safer than fossil fuel plants, and even safer than most renewables [10,11,12]. Fusion would be similar but with two extremely important differences – there is no chance of a meltdown at a fusion power plant, and the radioactive waste produced by a fusion plant would be both short-lived and low-level, becoming safe after around 100 years as opposed to thousands of years. Another important difference with fission is that the components needed to ignite nuclear weapons have no place at all in current fusion reactors, as Uranium is not required for their operation.

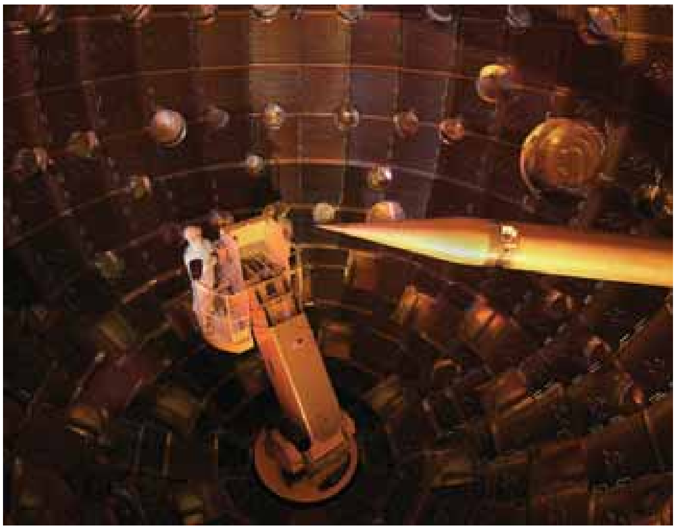
One of the two huge laser bays.

One of the criticisms that can be levelled at fusion is that we will have no need of it because renewables could supply all of our energy needs using currently available technology. However, realistic assessments of UK renewables do not predict more than 10-15% of our energy needs being met by them, they are land intensive, do not provide a consistent supply, and may be more effective if located in other countries. In truth a mix of energy supplies will, as now, be the most useful strategy.

Given the enthusiasm of scientists, and the potential benefits, why haven't we achieved fusion yet, and what progress has been made? To bring star power to Earth will undoubtedly be one of the most important breakthroughs in human technology there will ever be. Fusion fuel has the highest energy per unit mass of any fuel available in the Universe (a single kilogram of it releases the same amount of energy as burning 12 million kg of coal), and is the most common fuel in the Universe, so it will surely be an important primary energy source for humanity in the future. However, it was only in 1920 that scientists realised that fusion reactions powered the Sun. Controlled fusion experiments began in the 1940s and 50s and it quickly became clear that the challenges of containing the state of matter of which stars are composed, plasma, at the millions of degrees C° and densities up to ten times that of lead which are required for fusion reactions would require leaps in technology, and multiple generations. Just as it took thousands of years for the full power of coal to be exploited in the industrial revolution, and decades of refinement thereafter [12,13], the much more complex process of fusion has necessarily involved considerable time and effort to understand.

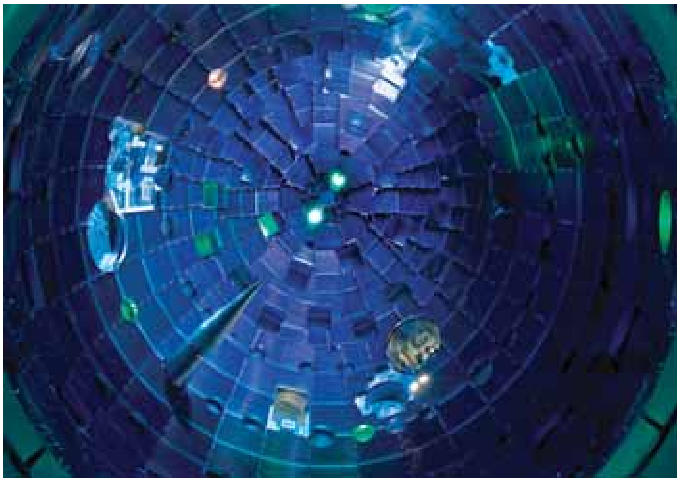
In the nine decades since fusion reactions were discovered, two methods for containment of the hot fuel have been devised – one using magnetic fields, the other using high power laser beams. Neither method has yet managed to achieve a net gain in energy but there are reasons to be positive about both. In the UK, the Joint European Torus used magnetic confinement of fuel to produce 65% of the power it consumed to operate, coming close to the magic 100% demonstration of technical feasibility. It is hoped that its successor, ITER, currently under construction in France, will be capable of reaching that goal in 2027 [14].

Laser fusion published its most successful result in 30 years of research in January 2014, in which the energy released by fusion reactions exceeded that put into the last stage of the compression of the fuel [15]. Though this result only represents an overall gain of around 1%, it is the first laser fusion experiment in which the fusion fuel was partially 'ignited'.



Scientists working inside the National Ignition Facility's target chamber. The fuel capsule, which is just millimetres in size but capable of releasing the equivalent energy of around 50kg of TNT, sits at the end of the long arm.

Full ignition would result in a gain well over 100%, so the excitement in the field is genuine. Laser fusion is a batch process, not unlike a petrol engine, in which a spark (provided by the laser) causes the fuel capsule, about the size of the pupil in your eye, to ignite and thereafter 'burn'. Burn means that self-sustaining fusion reactions propagate throughout the fuel, releasing energy. The machine responsible for the breakthrough is the National Ignition Facility (NIF), which is based at the US Lawrence Livermore National Laboratory. It has increased the energy produced from its experiments by orders of magnitude since opening in 2009.



Inside the National Ignition Facility's target chamber

Those in the laser fusion community are convinced that a machine with enough laser energy delivered to the fuel could cause a successful implosion of the capsule and high gain, and current work to improve gain is focused on how the energy is delivered. Their confidence is partly due to the pioneering work on fusion implosions by UK scientists Steven Rose and Peter Roberts in the 1980s [16].

Though much of this work, and the subsequent work led by US scientists, remains classified, a report on the US programme states that their experiments [17]

"...demonstrated excellent performance, putting to rest fundamental questions about the basic feasibility of achieving high gain."

In principle, the US National Ignition Facility has enough laser energy to get ignition, and is certainly making promising progress toward that goal, but other countries are fast catching up. France has almost finished its own reactor, Laser MégaJoule, while Russia and China have announced plans to build their own machines.

Though there is no ignition scale laser fusion experiment based in the UK, research councils have funded collaborative theoretical and computational work between UK and US scientists, and a US-UK memorandum of understanding was signed by the Minister, David Willetts, in 2011 [18]. There are currently only a handful of scientists directly involved in laser fusion in the UK, but relevant work has been conducted in the UK for many years. To capitalise on the early lead which the UK took in the field, and to take advantage of the close ties the UK has with the US programme, more UK scientists are desperately needed. The UK undoubtedly punches above its weight, particularly in the theoretical and computational challenges of laser fusion, but those competencies are threatened by the much larger, better resourced, teams of scientists that are operating in the US.

If the National Ignition Facility can achieve its goal with a significant contribution from UK scientists, then the UK will be uniquely placed to assist, or even construct, the next iteration of plant; a laser fusion reactor which would deliver power to the national grid.

Fusion is an important goal for humanity, and one in which the UK's scientists and engineers could play a large role. In the process of achieving ambitious goals where the nature of research makes outcomes and time scales uncertain, it is important to ask two questions. Is progress being made? And is the goal worth achieving? In the case of fusion energy, the answer to both of those questions is most emphatically 'yes'.

The small gold cylinder, just 8.4mm long, which holds the fuel capsule

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