Methods of producing nuclear fusion on earth

What Are the Methods of Producing Nuclear Fusion on Earth , and Will This Be a Viable Energy Source for Future Generations?

Nuclear fusion is defined as the process in which two small nuclei are fused together into one, larger nucleus. The energetic conditions necessary to achieve this type of reaction are extreme, combining high temperature with high pressure, rendering this stellar process exceedingly difficult to produce on Earth. Yet it seems as though this phenomenon may be the future of energy production; especially in this new era, when our traditional energy sources such as fossil fuels are both almost depleted and causing possibly irreparable harm to our planet and its ecosystems.

The reaction was first hypothesised in the 20s by many physicists including Arthur Eddington, who speculated that the source of energy of stars, which previously had been an unknown, was the fusion of hydrogen nuclei into helium nuclei. He knew that this process must release a significant amount of energy due to the earlier discovery by Francis Aston that the mass of a ^{4}He atom was only around 99. 2% of four ^{1}H atoms; which implied that if the hydrogen did combine, that there would be a large release of energy, due to Einstein’s energy mass equivalence equation, E = m c 2

equation, discovered only in the previous decade. [1] Of course, at the time of Eddington’s discovery, no one yet knew why the helium atom did not have the mass expected of it. As was later discovered, this was down to a ‘ mass defect’ that all nuclei have, that is directly caused by something known as nuclear binding energy. This is the minimum energy required to completely pull part an entire nucleus into its constituent particles, which are held together by the strong interaction. In general, however, only nuclei lighter than iron fuse, as when nuclei become any heavier than this, the binding energy per nucleon decreases and thus the reaction becomes endothermic; meaning that it requires rather than releases energy.

Fusion is widely proposed as one of the main solutions to the energy crisis based on its many theoretical advantages; especially when compared to fossil fuel and nuclear fission energy production. In terms of advantages over fission power, the fundamental difference between the two is that controlled fusion reactions have much lower potential for accidents, and in the rare case of an accident, the risk of danger would be much lower. This is partly due to the fact that if a fusion reactor is damaged or loses control, the fusion reaction would just stop within a short time span, as the precise conditions required to produce the reaction would no longer exist, and fusion in itself is not wholly self-sustaining. [2] Additionally, fusion reactors contain a comparatively small amount of fuel in relation to fission reactors, meaning that the fuel would burn out quickly, on the order of seconds. [3] Conversely, in a fission reactor, if control is lost, the chain reaction nature of induced fission can result in the reactor going super-critical, meaning that the number of reactions and therefore the energy produced would increase exponentially; resulting in a large release of energy in a small amount of time possibly in the form of an explosion – such as those produced by the original fission bomb used at the end of the second world war. Furthermore, fusion power does not have any dangerous radioactive products or reactants that require specialised disposal such as in fission reactors. This means there is little to no risk of radioactive sources impacting on the environment; in stark contrast to nuclear fission.

There are many necessary elements that factor into the control of fusion reactions inside a reactor. Most importantly, there is confinement. Confinement is the aspect of keeping the plasma fuel at the correct temperature and pressure conditions for a time that will allow the nuclei to fuse. Confinement itself can be achieved through three different methods. One method that can be utilised is inertial confinement, which works through use of lasers. In this form of confinement, a single pellet of usually deuterium fuel is compressed by lasers to a density and temperature high enough to satisfy the Lawson criterion – when the rate of energy generated through fusion reactions is greater than the energy lost to the environment. [4][5] Most forms of this method consist of a three-step procedure. Initially, the fuel is heated until the outer layer, or shell, is blown outwards by the heating, which reactively forces the remainder of the pellet to compress inwards, converging on the centre. This event should result in extremely high temperatures and densities near the centre of the plasma of nuclei. If these conditions produced by the compression are enough to satisfy the something known as the Lawson criterion, ignition can occur at the centre of the fuel, resulting in an ignition originating from the centre, moving outwards – eventually consuming all of the fuel. [4] An example of a facility which utilises this method of confinement is the National Ignition Facility in California in the US. [6]

Another form of confinement technology is magnetic confinement. In this method, the reactor takes the shape of a torus and the charged plasma particles rotate around the magnetic field lines inside the toroidal reactor. [7] As the temperatures necessary to ignite and sustain fusion reactions in the plasma (≈10^{6} K) are higher than any material used for containment could withstand, magnetic confinement provides a solution that would allow a fusion reaction to remain confined for a possibly longer period of time and could sustain a reaction that would last longer than that produced by inertial confinement. The greater freedom which this method gives also allows for various heating methods, an example of which is ohmic heating, where an electric current is passed through the conductive plasma – causing a heating effect. Other possible heating methods include radio frequency heating, where a radio or microwave frequency alternating electric field causes a heating effect in a material when passing through it, and also neutral beam heating, which involves firing a beam of high-energy neutral particles into the confined plasma, causing a heating effect through particle collisions. [8] One of the many advantages of this confinement method is that the fusion reaction between deuterium and tritium, the two types of hydrogen nuclei used in this type of fusion, release most of their energy in the form of neutrons with high kinetic energies. The energy from these high energy neutrons can be collected relatively easily, through collisions with lithium nuclei contained within a blanket surrounding the reactor – producing heat energy. As an additional benefit, these collisions can also produce more tritium nuclei, allowing for the prolonging of the fusion reaction inside the toroidal reactor. [9] The main form of toroidal magnetic confinement reactor and the current leading candidate for a practical fusion reactor is the tokomak, the first of which was hypothesised and created by Soviet researchers in the 1950s and 60s. This came after the failures of other types of reactors which used the magnetic confinement method such as the z-pinch and stellerator. [10] In current times, the tokomak is seen to be the most likely concept to succeed and as such is the type of reactor that the International Thermonuclear Experimental Reactor (ITER) project will be using. [11]

The third and final method of confinement is known as electrostatic confinement, which in principle is slightly similar to magnetic confinement but utilises electric fields rather than magnetic fields. The main variation of the use of this method is a device known as a ' Fusor'. These fusors are based on the concept of a potential difference being applied between concentric, translucent grids, causing charged particles of fuel being focussed inwards. The ions will accelerate towards the bottom of the potential and converge, resulting in a high temperature, high density core of either pure deuterium or a mix of deuterium and ^{3}He. [12] However, these types of fusion reactors are not currently seen as more viable or operationally superior to the toroidal magnetic confinement reactors such as the tokomak.

As briefly touched upon previously, there are three distinct fusion reactions that can be used in fusion reactors, each with their respective advantages and disadvantages. Widely regarded as the easiest to produce and, coincidentally, the one, as mentioned, that is commonly used in toroidal magnetic confinement reactors such as the tokomak – is the deuterium-tritium reaction. It is viewed as such, partly due to the fact that this reaction has a higher probability of collision in a plasma than the other two, and partly due to the fact that it is easier to sustain, as the lithium ‘ blanket’ used to capture useful energy from the reaction also produces more tritium as a bi-product. This is even more helpful when it is considered that tritium is the most difficult of the three elements to obtain, due to its relatively short half-life of approximately 12 years. [8] There are, however, drawbacks to this particular fusion reaction. Firstly, it produces a large number of neutrons, which over time will cause neutron activation, resulting in the weakening of the structural integrity of the material used to contain the fusion; meaning that it cannot be used long-term in a fusion reactor. Secondly, the handling of tritium is unavoidable. This is a disadvantage as handling tritium comes with the caveat of the possibility of leaking, which is particularly dangerous as it could result in a possibly large release of radioactive material into the environment. [13]

The fusion of two deuterium nuclei is regarded as the next easiest fusion reaction to produce after deuterium-tritium and is often the fuel of choice in inertial confinement fusion. However, this reaction has a much smaller Q-value than most other fusion reactions, especially deuterium-lithium, meaning that the overall energy absorbed or released in the reaction is much smaller. This is particularly disadvantageous when considering that deuterium fusion also requires more energy to induce – rendering it a less time efficient reaction. In terms of advantages, this reaction does not cause as much damage to its containment material as it does not produce high energy neutrons such as in the deuterium-tritium reaction, which in fact means that a solely deuterium fuel allows for the use of materials currently employed in the fission power industry. [14] However, deuterium-tritium at this point in time is viewed as the most likely fusion reaction to be successful in the future and will likely be used in the ITER project based in France.

To conclude, there are many different methods of inducing fusion reactions on Earth, and so far, the most promising seems to be using magnetic confinement in a tokomak. This method is being pursued by researchers all over the world, mainly in the form of the multi-billion-pound ITER project. The pursuit and study of fusion energy is objectively crucial, as it could provide a relatively safe, practically limitless source of energy for the future; meaning that trade-off decisions involving environmental damage and safety would no longer be necessary for future generations.

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