Thermonuclear fusion

Second Year Summer Essay

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Introduction

Thermonuclear fusion is the term applied to the process of combining two nuclei together. This process is useful because it is a method of releasing usable energy in an environmentally friendly way. The energy released in this process has the potential to fulfil mankind's ever growing requirements.

This essay will outline the characteristics of thermonuclear fusion, different ways of artificially inducing fusion and finally the advantages, disadvantages and future of fusion research.

What is Thermonuclear Fusion?

Thermonuclear fusion is actually quite similar to most chemical reactions in that two initial 'reactants' come into proximity to eachother and join together to create a number of new products. Unlike chemical reactions, thermonuclear fusion is the fusion of the nuclei rather than atoms and molecules. Because of this difference there are different rules which must be obeyed and different problems which must be overcome.

The foremost problem fusion faces is that the two reactants are both nuclei – as such they are both positively charged bodies which we want to force together. This presents a problem as similar charges repel eachother. It is particularly a problem because to fuse the nuclei, we need to bring the nuclei to within about $2\times10^{-15}m$ of within eachother. Only nuclei at extremely high temperatures have the required kinetic energy to overcome this potential barrier and so this is where the term *thermonuclear fusion* comes from.

Thermonuclear Fusion is a process which transforms matter into energy; the mass of the initial reactants is greater than the mass of the final products – and, as Einstein showed the world, the energy associated with a material is proportional to the product of the mass of the material and the square of the speed of light; $E = \gamma mc^2$. It is this *mass deficit*[1] which allows fusion to release energy.

The physics of fusion

Whilst nuclear physics seems rather exotic and somewhat strange, in actual fact it is as natural as photosynthesis in plants. Nuclear fusion is the process by which the stars exist. Our own sun is a prime example of natural nuclear fusion.

Artificially induced nuclear fusion usually involves the fusion of deuterium and tritium nuclei. These are simply isotopes of hydrogen and are available in everyday water supplies. It is this abundance of the required reactants which makes fusion so attractive. Unlike thermonuclear fission, there is no mining or expensive and potentially dangerous enriching of materials. The reason for the use of deuterium and tritium rather than hydrogen is that it is easier to fuse nuclei which are neutron rich; as the charge density is reduced by the presence of the additional neutrons.

As previously stated, the sun uses fusion to generate all of the heat and light that we use everyday. This is done by *gravitationally confining* the hydrogen isotopes. That is to say that the density of the isotopes is so great that the attractive force due to gravity overcomes the coulomb repulsion between the isotopes. It is this seemingly simple situation which leads to the process of nuclear fusion to occur and life to exist on Earth.

The fusion of hydrogen in the sun may proceed through a reaction known as the proton-proton chain. This is where four hydrogen nuclei (protons) are fused to produce a helium nucleus (an alpha particle), two positrons and two electron neutrinos;

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}e^{+} + 2\nu_{e}$$

Observations of this process yielded the neutrino problem[2, 3] which was answered after plaguing the physics community for approximately thirty years.

Unfortunately for physicists, we cannot recreate the environment described above as this would require vast amounts of hydrogen isotopes which simply do not exist on Earth. It is the mission of fusion research to find alternative methods of bringing the hydrogen isotopes close enough to eachother to allow fusion to occur.

There are currently two different approaches to forcing the reacting nuclei together. The first is to take a sample of the material and to raise the sample's temperature it using lasers in a very short period of time. By doing so, the centre of the sample cannot expand outwards, due to the surrounding material, and so is compressed to the point where fusion occurs. This is known as *inertial confinement*. This process requires many lasers to strike to material from numerous different angles. Examples of this approach include Shiva and NOVA (both based at Lawrence Livermore Laboratories in California) [7].

The second approach is to make the material follow a given path and to attempt to compress this path so much that the nuclei fuse. There are a number of different designs for these paths (which are closed loops) and they include a torus shape and a spherical shape. The material is forced around these paths by using a combination of electric and magnetic fields and as a result is known as *magnetic confinement*. Past examples of such fusion reactors have included JET[6] and TOKAMAK[5] and current projects include ITER[4]. These designs have become increasingly effective not only as our understanding of fusion has developed but also as our ability to create the desired magnetic fields has improved.

As the nuclei are charged bodies in a magnetic field they are subject to a force in accordance with Fleming's right-hand screwing rule. The magnets that do this job are known as Toroidal Field Coils. However as the nuclei are moving charged bodies, they generate their own magnetic field (again in accordance with Fleming's right-hand screwing rule). The result of this field is that the previously (almost) perfect circular motion of the nuclei now has 'dents' and 'bumps'. This motion is rather similar to the motion of the Moon orbiting the Earth which orbits the Sun. This motion of the nuclei is not particularly desirable for fusion and so Poloidal Field Coils are used to correct it (See Figure 1).

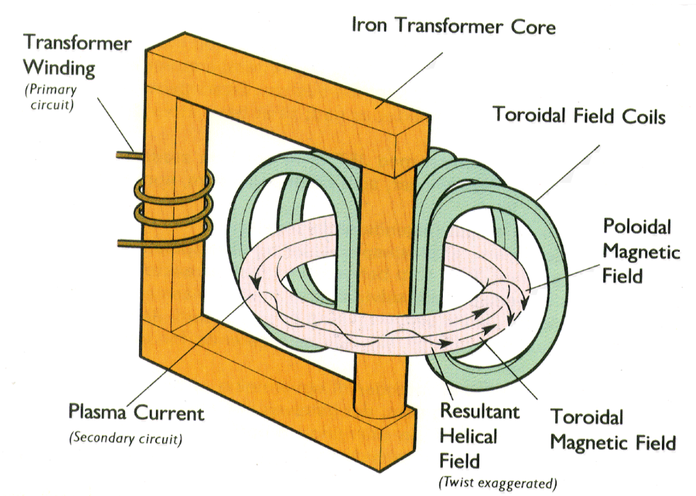

Figure 1: Diagram of magnetic confinement reactor showing toroidal and poloidal magnetic fields[8]

Out of these two approaches, the second magnetic confinement method is the more effective and as a result is the most popular in the field of fusion research. However the result of each method is identical; hydrogen isotopes undergo fusion. This process can be represented by a number of reaction equations[1];

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H + 4.0\,\mathrm{MeV}$$
$$^{3}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\,\mathrm{MeV}$$
$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3.3\,\mathrm{MeV}$$
$$^{3}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{1}H + 18.3\,\mathrm{MeV}$$

One of the possible products of these reactions are neutrons, which have no overall charge and so are not affected by the magnetic fields discussed previously. These neutrons are a loss of energy and so to recoup some of this energy the reactor is surrounded by a *lithium blanket.* This surrounding lithium absorbs the neutrons and as such the temperature of the lithium increases. The energy can now be recouped, by extracting the heat in conventional methods, and can be used as appropriate.

The advantages of thermonuclear fusion

As previously stated, thermonuclear fusion presents an opportunity to provide the required energy in an environmentally friendly way. There are a number of reasons for fusion being environmentally friendly.

Firstly the reactants used can be extracted from water supplies, given that most of the surface of the Earth is covered in water, the supplies of hydrogen isotopes are abundant and should be easily accessible. The comparatively safe refining of this water would require a refining plant - however such a plant would have much less of an environmental impact than other means.

Secondly reactors in which the refined isotopes of hydrogen are placed will require the use of materials, however such uses are comparable to other reactors used in power stations and so whilst they must be considered, are not a major issue.

Also, the products of the reaction are simply helium, hydrogen or neutrons. Unlike products of other processes such as carbon dioxide or radioactive materials, the products of fusion have no particularly undesirable effects.

The disadvantages of thermonuclear fusion

The main disadvantage of fusion so far, is that nobody has been able to make a reactor that can consistently achieve *breakeven*. This jargon means the level at which the energy output of the reactor equals the energy input to the reactor. Obviously a reactor operating at breakeven would provide no more energy than we originally had and so any reactor which is to be useful must achieve a greater level of efficiency than the breakeven. This is the area in which fusion research is currently most concentrated on.

There are a number of issues facing nuclear fusion which must be overcome before fusion research can provide an alternative to current methods of generating electricity. These issues are not actually disadvantages that are inherit to fusion and so will be discussed in the following section.

The Future of fusion

Currently there is a number of exciting fusion projects underway. Currently the International Thermonuclear Experimental Reactor (ITER) is under construction in France. This is a joint project between the European Union, the People's Republic of China, the United States of America and Japan. This 500MW reactor is a torus design measuring 12 metres across, 5 metres tall and the internal diameter of the torus is 3 metres. This means that the size of the plasma chamber is about the size of a house (See Figure 2).

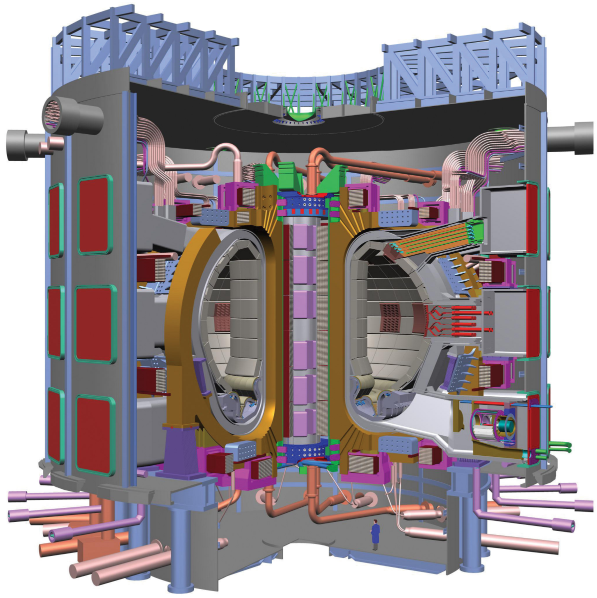
Figure 2: Diagram of ITER plasma chamber and magnetic coils[9]

As its name suggests, ITER is not intended to generate electricity; it is an experiment in fusion. It is expected that, after ITER's lifetime, another reactor, DEMO, will be built which shall be larger than ITER and shall generate electricity. This is expected to be able to have an output of 500MW of electricity which is comparable to power stations currently in operation in the real world today!

Over the past fifty years fusion research has improved steadily and we are nearing the breakeven point. The latest estimates indicate that fusion reactors will be providing domestic energy by 2050.

Once we reach this point, it is likely that fusion research will still continue with the aim of producing more efficient and reliable reactors. In an ideal world this would be the end of mankind’s dependence upon carbon fuels, however there are other considerations to be made.

Firstly economics will have the biggest impact on the use of fusion reactors - if it is not economically viable to utilise fusion research then it is unlikely that it will be used. However the economic situation will change in favour of nuclear fusion as carbon fuels become increasingly sparse. Therefore, over time, the economic problem facing nuclear fusion will almost certainly solve itself.

A second issue for the future of nuclear fusion will be the size of the reactors; currently the biggest use of carbon fuels is in vehicles such as cars, trucks, boats and planes. Nuclear fusion can only be implemented if the size of the reactor is reduced enough to fit inside the smaller of these vehicles. A possible solution to this problem could be through researching more efficient means of storing electrical energy generated by a fusion reactor, although given the progress of electrical cars this will require some time.

However even in the face of these issues, thermonuclear fusion certainly does present a truly viable option to fulfil humankind's need for energy in a way which will not damage the environment.

Beyond the coming decades research will undoubtedly continue in the field of fusion, one possible area is to research into alternative nuclei that could undergo fusion, one possibility is a rather more exotic hydrogen molecule; this process is known as muon-catalysed fusion as muons replace the molecule's electrons. As the muons have a greater mass than the electrons the probability to fuse increases. However, as stated before, such methods will require extensive research.

Conclusion

Thermonuclear fusion appears to be an ideal method of generating electricity for our ever growing needs. The materials are widely available and the impact upon the environment is so minimal that it could be argued that fusion research will produce some of the most important developments of the 21^{st} century.

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