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INFORMATION FUSION

Fusion Energy: An Option for the Future

Fusion energy from the sun has warmed the earth for billions of years. Today, scientists and engineers have achieved the first demonstrations of a process for releasing fusion energy similar that which takes place in the sun. This opens up the prospect of a virtually unlimited resource for the generation of electrical power using fuels which are readily available world-wide.

Without the continuous flow of heat from the sun, our earth would be frozen and lifeless. The sun gets its power from the fusion of hydrogen into helium: every second 600 million tons hydrogen are consumed, equivalent to a hundred times the mass of the largest pyramid in Egypt, or in one minute, about the same as the mass of the Matterhorn above Zermatt.

The sun has been converting hydrogen into helium for billions of years and astrophysicists assure us that it will continue for a few billion years more before the hydrogen supply is exhausted.

About one half of one percent of the mass of the hydrogen fuel is converted into energy (in accordance with the well-known Einstein relation between mass and energy) and escapes as electromagnetic radiation, i.e. light. Almost all of this is lost in the depths of space, less than one part in a billion falling on the earth.

Nevertheless, this infinitesimal fraction of the sun's output provides a huge power input to the earth: 175 million billion watts. This power is

The sun's fusion energy which warms the earth is the origin of all renewable energies. Fusion R&D aims at providing on earth a safe, environmentally friendly energy source.

distributed around the globe by the earth's rotation, but is a maximum near the equator, where at noon it reaches approximately one kilowatt per square metre. At the latitudes of central Europe the solar power input is considerably weaker, the annual average being 100 to 250 watts per square metre. Taking into account the efficiency of photovoltaic solar cells, an average of a few tens of watts of electricity can be generated per square metre, with large daily and seasonal variation.

Fusion on earth

It is impossible to reproduce on earth the same mechanisms which create energy at the centre of the sun. The sun has a mass about 330000 times that of the earth and therefore a much stronger gravitational force. This compresses the hydrogen atoms in the sun's centre so close together that the fusion of the nuclei of adjacent atoms is facilitated. Each of these fusion reactions liberates about ten million times the energy of a typical chemical reaction. In a small volume, the reactions don't happen so often, but, because the total volume of this "solar furnace" is so huge, overall an enormous amount of power is generated.

There is, however, a much more efficient variant of hydrogen fusion which can be used for energy production (in particular, for electricity) by mankind – the fusion of deuterium and tritium. These are the heavier, and less common, isotopes of hydrogen. There are about 35 grams of deuterium in every cubic metre of water. Tritium occurs in nature only in trace quantities because it is radioactive, with a half-life of about 12 years. However, it can be produced artificially from lithium, which is one of the most abundant light metals in the earth's crust. So, the primary fuels for fusion on earth are practically inexhaustible and are readily available everywhere: in the seas, in lakes, in rivers, and (for lithium) in rocks as well.

The amount of fuel needed in a fusion power station is very small. The fusion of about a thousand tonnes of deuterium and tritium would satisfy the annual energy demand for all mankind. Two to three tonnes of deuterium and lithium would be sufficient to supply a one gigawatt power station. Compare this with about 100 tonnes of enriched uranium for an equivalent nuclear fission power station or about 2.5 million tonnes of fuel for a coal-fired power station. All the electricity consumed each year in one of the large EU member states could be generated from a few lorry loads of deuterium and lithium.

Progress of research

The construction of a fusion furnace is a difficult task. However, in the past decade, fusion researchers have made remarkable progress in realising this process. This has been part of a programme of research, stretching over several decades, which has seen a unique degree of European and international co-ordination and co-operation. The research has now reached the point where it has become possible to prepare the essential further step: the demonstration of the scientific and technical feasibility of a fusion energy system in actual power station dimensions.

Over the decades of research the scientists in their laboratories have learnt, step-by-step, how to create the conditions necessary for fusion, such as the achievement of extremely high temperatures. In 1991, substantial fusion power (1.7 MW for a short time) was produced for the first time, using deuterium and tritium fuels in an experimental process which can be further developed for use in a fusion power station. This important milestone for fusion was achieved at JET (the Joint European Torus), a machine located near Oxford in the UK and built by scientists and engineers from all over Europe. In 1997 the successful experiments in JET were further extended when fusion power production in the ten-megawatt range was obtained for some seconds, with a maximum of 16 MW. This power output is already a large

JET (near Oxford) is operated jointly by Europe. It is the largest existing and most powerful fusion experiment worldwide. In 1997 JET achieved the production of 16 MW fusion power.

fraction of the power required to heat the plasma to fusion temperatures. With these, and many other scientific results, the European researchers have clearly exceeded the original aims of the JET machine. It is now possible to move forward to a machine with fusion power in the hundred megawatt range and a large “power amplification”, that is, power production much greater than the input power to the plasma furnace. This “next step” will demonstrate scientifically that fusion has the potential to become a useful energy producing system. Evidently, a machine is needed which is larger and more powerful than JET. A considerable further investment in research and development is still required over some decades before fusion will be available to society as an energy option for commercial use.

Are the development costs of fusion justified? A safe, reliable and secure energy supply can only be guaranteed by a combination of independent, environmentally friendly energy systems; and fusion is one of the very few available options. Taking a global perspective with a time horizon beyond the next few decades, the growth in world energy demand and the need to curb the greenhouse effect tell us that the answer must be "yes".

Nuclear fusion can be realised also by another scheme in which a pellet of a few mm diameter, filled with fusion fuel, is irradiated by high power lasers or atomic beams. The pellet is compressed and strongly heated in its centre so that fusion reactions are initiated. The pellet then explodes during further heating by the fusion burn. About 10 – 20 pellets would have to be irradiated per second. This method is called “inertial confinement” since the fuel is confined only as long as its own inertia inhibits the thermal explosion which is for a billionth of a second.

Magnetic confinement

In principle, fusion is possible with all the light elements. The requirement is that the atomic nuclei are given sufficient kinetic energy to overcome their mutual electrostatic repulsion when they collide. This kinetic energy is achieved by heating the fuel to very high temperatures. But, even for the “easiest” reaction, that between deuterium and tritium, a temperature of more than one hundred million degrees is required for a fusion reactor. (In the centre of the sun the high density and the enormous volume permit the more difficult fusion reaction of the lightest, normal hydrogen isotope into helium at a ten-fold lower temperature.) Of course, the gaseous fuel, which is completely ionised at these temperatures and is called “plasma”, must not be allowed to come into contact with the walls of the reaction container, since some of the surface layer of the wall would be evaporated and the plasma would be immediately cooled to a temperature too low for fusion reactions to occur. The solution is to keep the hot plasma away from the walls using strong magnetic fields. This is called "magnetic confinement". The plasma is held in a doughnut shaped vessel (a "torus"), since this topology lends itself to a confinement with magnetic field lines forming closed loops.

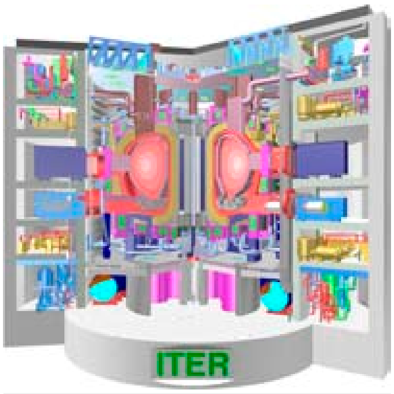
150 million degrees & 1.5 metres

The performance of the magnetic insulation is astonishing: fusion researchers have achieved temperature gradients of more than one million degrees per centimetre. In other words, a temperature difference of 150 million degrees can be maintained with insulation just one and a half metres thick.

The doughnut shaped vessel of a fusion reactor is actually a high vacuum chamber, because the plasma has a density only one millionth that of normal air. The combination of the extreme fuel temperature with this very low density results in a plasma pressure of several atmospheres. How big must the radius of the plasma doughnut be? The magnetic insulation needs 1.5 m and in the centre there must be enough volume of hot plasma to achieve sufficient fusion reactions for the desired fusion power. A fusion reactor with one gigawatt (1000 megawatt) electrical output is likely to need a vessel where the cross-section radius is about 3 metres and the radius of the doughnut is around 8 metres. This corresponds to a plasma volume of about 1000 cubic metres, which is in fact smaller than the combustion chamber of a brown-coal power station. The present prototype machines, although big enough to permit the investigation of the characteristics of the plasma under fusion conditions, have much smaller volume: JET is just under 100 cubic metres, and the largest second fusion experiment (the Japanese JT-60U) is slightly smaller.

To get the fusion reactions started, the fuel is heated by microwaves and other methods until the necessary temperature is reached. Once the fusion "burn" starts, it creates "ash" in the form of helium nuclei (alpha-particles). These have very large kinetic energy, equivalent to a temperature of about a billion degrees. Being electrically charged, they are confined in the plasma by the magnetic fields and they transfer energy to the cold, freshly injected deuterium and tritium fuel, heating it to the temperature required for fusion. This allows the external heating to be reduced, or even switched off completely.

The alpha-particles are not the only product of the fusion reactions: a high energy neutron is also released by each reaction. These neutrons, which carry 80% of the released fusion energy, are not confined by the magnetic fields. They pass straight into a blanket lining the walls of the combustion chamber where they deposit their energy and are absorbed. A circulating coolant in the walls is thereby heated. This heat is transferred via heat exchangers, steam is generated to drive turbines, and electricity is generated just like in a conventional power station. Despite the high temperatures in the burn chamber, the waste heat from fusion will be the same as that of a conventional (e.g. coal-fired) power station.



Cut-away model of the International Thermonuclear Experimental Reactor (ITER) with 6.2 m radius and a projected fusion power of 500 MW. Inside the D-shaped superconducting coils the vertically elongated plasma doughnut can be seen.

Inherent safety aspects

The primary materials for the fusion fuel are deuterium and lithium. They are not radioactive and can be transported without problems to the power station. The "ash" is the noble gas helium, which is also non-radioactive.

Compared with nuclear fission the processes taking place in a fusion power station are more complex. However, the system functions according to a very simple principle: a fusion power station is like a gas burner fed from a separate fuel supply. Only the small quantity of fuel needed for the next few seconds of operation is injected into the burner. This means that the fusion reactor can be shut down very quickly if there is any disturbance to normal operation. The presence of only a few grams of fuel in the plasma is a fundamental safety feature of a fusion power station. In addition, the fusion process itself does not produce any radioactive waste.

A unique feature of a fusion power plant is that the radioactive fuel component, tritium, is produced in a lithium-containing blanket around the plasma chamber, i.e. within the power station itself. The neutrons released by the fusion reactions react with the lithium in the blanket, transforming some of it into tritium. Thus fusion has the significant advantage that the only radioactive component of the fuel is both produced and burned in the power station.

It was already noted above that if the plasma comes into contact with the wall, small quantities of evaporating wall material are sufficient instantly to cool down the plasma and terminate the fusion process. In the same way, the smallest leakage of air into the combustion chamber will terminate the fusion process immediately. The thermal energy content of the plasma is so small that melting of the plasma container, i.e. "core meltdown", is impossible.

Exhaustive safety studies have shown that a fusion power station can be operated without risk of radioactive emissions harmful to humans and the environment. The maximum amount of tritium which could be released in any conceivable accident is so small that the area surrounding the power station would not need to be evacuated. Finally, it is worth noting that a fusion power station does not need any radioactive substances other than the tritium which is produced and burned there.

Materials and waste

The neutrons produced by the fusion reactions carry a high energy, so as well as breeding tritium in the lithium blanket, they also interact with the walls of the plasma chamber, changing the characteristics and activation of the wall materials.

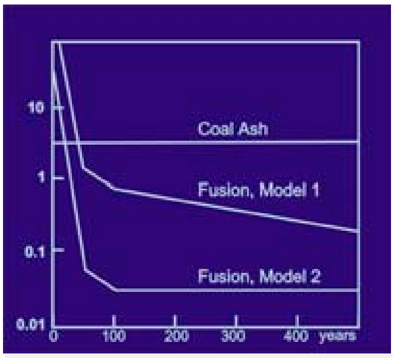
The expected quantity of these activated materials is not very different from that which develops in the case of a comparable nuclear fission power station. The amount of radioactive waste generated by a fusion reactor depends substantially on the materials which are used for the construction of the power station core. If normal steel were to be used, the result would be very long decay times for the radioactivity because of some of the alloy components and impurities which are usually found in steel.

A substantial research task is therefore the development of low activation iron-based steel as well as the investigation of titanium and chromium alloys. Ceramics and fibre-composite materials are also being examined for their long-term potential.

The results from current material development studies lead us to expect that the radioactivity of the waste from fusion power stations will decay rapidly, and after about one hundred years will fall to a level lower than the natural level of radioactivity in the ash which makes up the waste from a coal-fired power station. Thus the reuse or long-term storage of materials from a fusion power station should not cause any substantial problems. Additionally, a fusion power station will generate virtually no gaseous radioactive waste to threaten the wider population, either in normal operation or in the case of an accident.

The future

Fusion research is an interdisciplinary programme, whose progress depends on leading-edge research in many different areas. Demanding engineering techniques include superconducting technology, the fabrication of large magnetic field coils, the generation of high frequency, megawatt level electromagnetic waves, and accelerator technology for plasma heating systems. The understanding of the physical behaviour of plasmas at very high temperatures, the physics of high power electromagnetic waves, chaos research and non-linear dynamics of systems, surface physics and solid-state physics, the control of complex systems, and the development of plasma measurement techniques are all required. Sophisticated computer technology and advanced numerical techniques are needed in areas such as plasma



Relative comparison of the radiotoxicity of coal ash and fusion waste according to two models with conservative and more optimistic assumptions on the progress in materials development for fusion. Horizontal axis: years after shut down of the power station.

control using complex feedback systems. Success in many of these areas depends on a close interaction with both basic physics research and various areas of applied research. A key area of work for the long-term future is material research, since the development of highly resistant, low activation materials for use in the reactor core is important for both the ecological and economic aspects of a fusion power station.

Fusion research is an undertaking which requires a sustained long term effort on a large scale, and therefore it is expensive. The successes achieved to date show that we are ready to demonstrate the scientific and technical feasibility of fusion by a further major experiment which is essentially the "core" of a fusion power station. Construction of such a device will last about ten years, and the research and optimisation of the various processes are estimated to last about another fifteen years. In a subsequent, partly overlapping step, a fusion core will be tested by integrating it into a complete, electricity producing power station which will undergo a period of optimisation and evaluation. This will require about the same length of time again, after which the commercial exploitation of fusion can begin. Altogether, fusion could be available as an energy option for the market around the middle of this century.

The achievements of fusion research and the well-defined technical perspective for the next steps show that fusion researchers are on the right track. The success of fusion development, and the need to guarantee a long-term, safe, environmentally friendly energy supply for a growing world population, are the reasons why Europe and the large nations of the world are pursuing the development of fusion as an option for the future.

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