Analytical Study of the Development of Nuclear Fusion Reactors as Potential Source of Energy In the Future

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Abstract

In the present World scenario, one of the most pressing problems that the human civilization is facing is of the rapidly depleting sources of energy. The Industrial revolution in the early 19th century has increased man's dependence on machines and the industry. Hence in this brash rush of Industrialization the consumption of Fossil Fuels like coal and petroleum has increased to such a great deal that the known reserves have reached an all time low.

Thus there is an inevitable need for developing alternative sources of energy in order to bridge this hiatus between the rapidly increasing fuel demand and the depleting resources available. In this paper, we have tried to analyse the potentials of Nuclear Fusion Reactors as a reliable alternative to overcome this energy crisis. Though the theories propounded are still in the state of infancy, they surely hold relevance for satisfing the fuel demand in the future in both on earth as well in space stations. Furthermore, the world environment dectates that any future fuel should be clean and non polluting.

We know that Fusion, a source of the sun's energy offer a clean, potentially limitless source of electricity and power. Hence a magnetic fusion reactor by using plasma would manage to bring about the nuclear fusion reation in a controlled way. Plasma is a new state of matter in which most of the atoms are ionized due to some sort of `violence' and breaking away of the originally bound electrons.Within the plasma, colliding deuterium and tritium nuclei would fuse into helium nuclei and release energy to be converted into electricity.

Introduction

The concept of generation of usable energy from the nuclear fusion reactor is still at its state of infancy. Though both Bose and Eistein , in 1925 predicted the condensation of atoms into super dense states but still even after 76 years of extensive research the idea of a nuclear fusion reactor has not been physically implementable. Though nuclear fusion is the primary governing factor in the nuclear reactor design but a number of complex systems and their analysis need to be incorporated for its success.

Currently, a number of significant projects are being persued individually by the developed nations like the SST project, the Magnetic Mirror project and the combined efforts of scientists and governments from all over the world pooling their intelligence and resources to develop the International Thermonuclear Experimental Reactor (ITER).

Nuclear Fusion

Nuclear fusion is a process in which light nuclei fuse together to form heavier ones, releasing a large amount of energy:

${}^{2}D$	+	${}^{3}T$	$\longrightarrow$	$4He$	+	n	+	17.6MeV
(Deuterium)		(Tritium)		(Helium)		(neutron)		(energy)

In this Fusion reaction, the deuterium and tritium collide and recombine to form a helium nucleus and one neutron, releasing energy in the process. This Fusion Reactions accompanies the decrement in mass which is converted into the kinetic energy of the newly created nucleus. The tritium in the reaction is a radioactive element which is not available in the natural stateand it is produced by the reaction shown :

$$N \quad + \quad 6Li_3 \longrightarrow {}^{3}T \quad + \quad 4He_2 \quad + \quad 4.78MeV$$

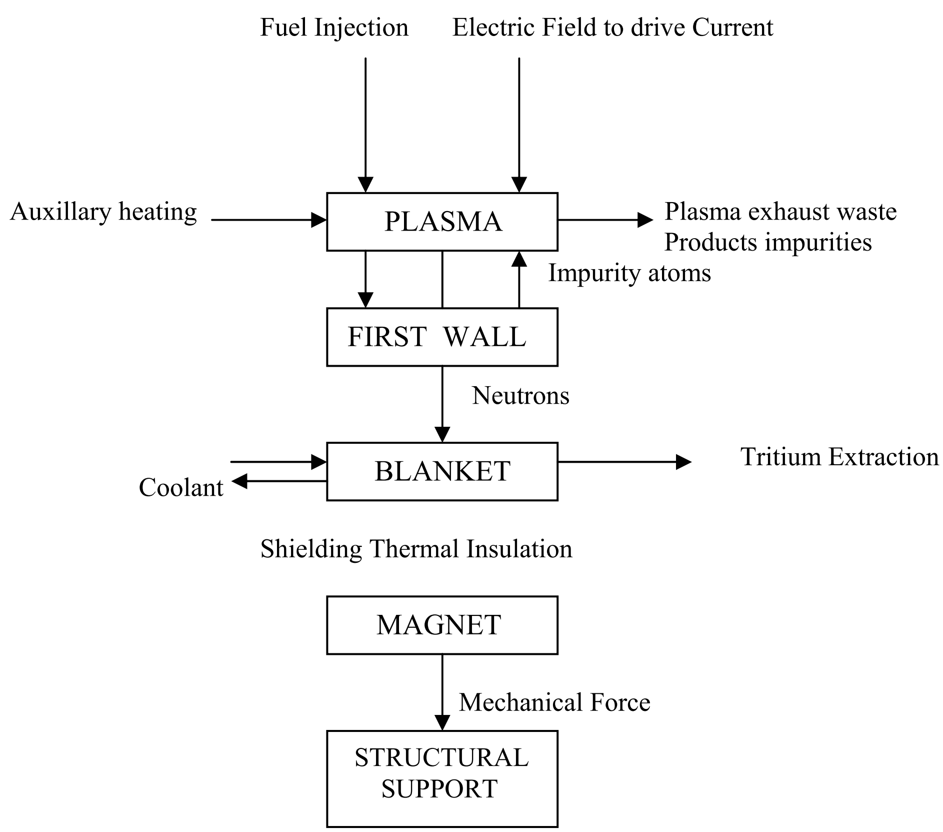
The major contradiction faced by this concept is from the Coulomb Laws stating that two like charged particles repel each other. But present research highlights that, if enough energy (0.28 MeV) is provided then the charged nuclei would experience short range nuclear ' strong force', which will take over and bind the two deuterium nuclei into a single new nucleus. Besides, if the experiments are conducted with accerated nuclei, nuclear reactions can take place at detectable rates even when the energies are considerably below those corresponding to the top of the Coulomb barrier. This effect is referred to as 'Mechanical tunneling', or 'Quantum Tunneling'. Wave Mechanical Tunneling takes place as a result of specific dynamic relationships which develop and exist between the interacting nuclei. Current theories have all indicated that quantum tunneling,, takes place in accordance with certain mathematical probability functions. To date there has been no real viable theory which has provided a concrete reason why quantum tunneling takes place at all. In fact, researchers have been puzzled because the fusion cross-section of low energy deuterons have been higher than theory predicts. Current theories have permitted no mechanical or physical explanation for this behavior. That is, tunneling appears to occur, and the why's are hidden in the statistical maze provided by probability mathematics. Quantum mechanics whose principle of complementarity implies that nothing can be known about particles between acts of measurement also sets artificial limits to human knowledge of the basic structure of and interaction of matter. It is obvious that when two nuclei undergo fusion to a bound state they are in a more ordered state than they were in previously as individual particles.

Working and Design

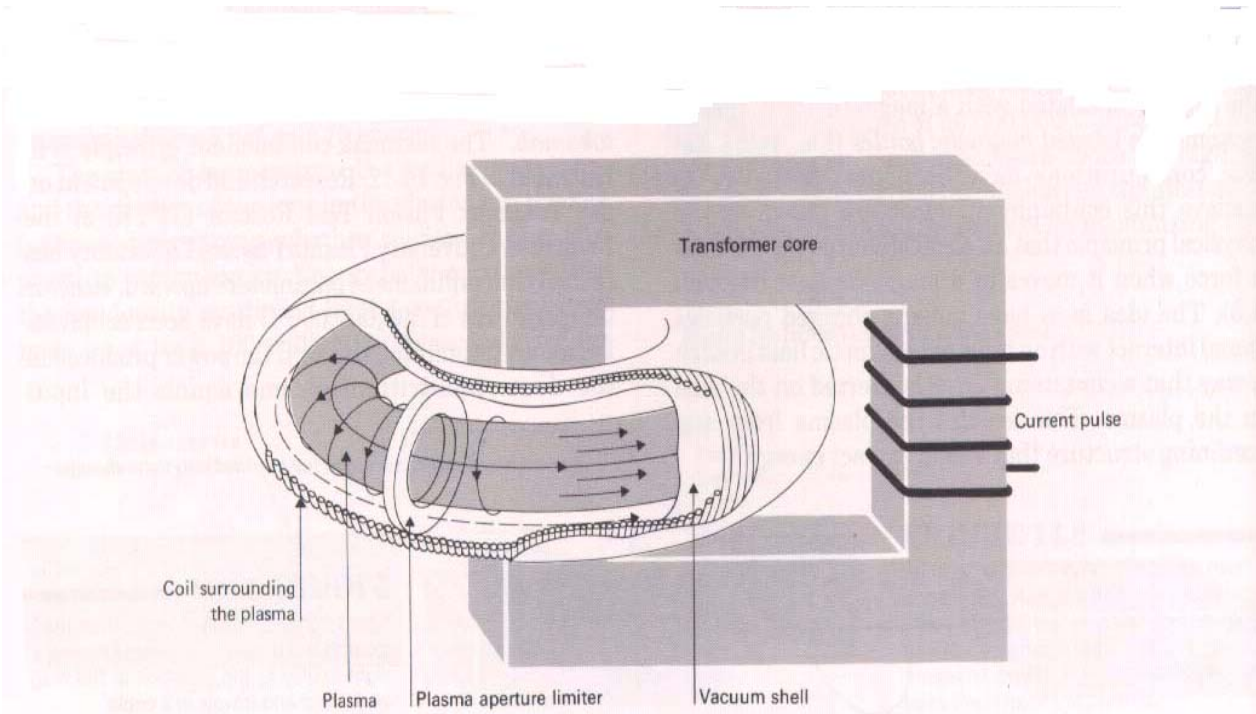
Significant research is on for the development of the nuclear reactor, one of the major projects most successful till date is the Steady State Superconducting Tokamak (SST-1) which is currently under fabrication at the Institute for Plasma Research (IPR), Bhat, Gandhinagar.

For developing a nuclear reactor it is important to first analyse the steps of its functioning and design. First it is necessary to comprehend the development of the plasma or charged state which is to be utilized as the nuclear fusion reactor fuel. **Plasma** is a newly developed state of matter in which most of the atoms are ionised due to some kind of 'violence' and breaking away of original bond electrons. The *First* step is to start with a reacting Plasma which is emitting energy in the form of neutrons, charged particles and various forms of photons. The *Second* step is to surround the Plasma with a solid wall which absorbs the charged particles and photons as well as providing a vacuum for the Plasma to ignite in a magnetically confined system. This wall will absorb about 20% of the energy from the Plasma and must be cooled. *Third* step is to surround the vacuum wall with a moderator to slow down the neutrons, a reflector to reduce the leakage of neutrons and a coolant to carry the heat away. The region should also contain the deuterium-tritium mixture so that the reaction can be continued. Approximately one metre of the Lithium blanket and the first wall is required to absorb about 97% of the heat produced from the Plasma. Unfortunately some neutrons and Gamma rays will escape, and the magnets must be protected from these sources of irradiations. This protection is accomplished by surrounding the blanket with a shield, that completes the moderation of these neutrons that escape and absorbs the Gamma rays emitted from the blanket. This shield also serves as final radiation, protection for personnel in the plant. Outside the shield will be located the magnets, fueling equipment, heat exchangers, tritium removal devices and other equipment associated with the plant.

Schematic representatoin of main components of a reactor

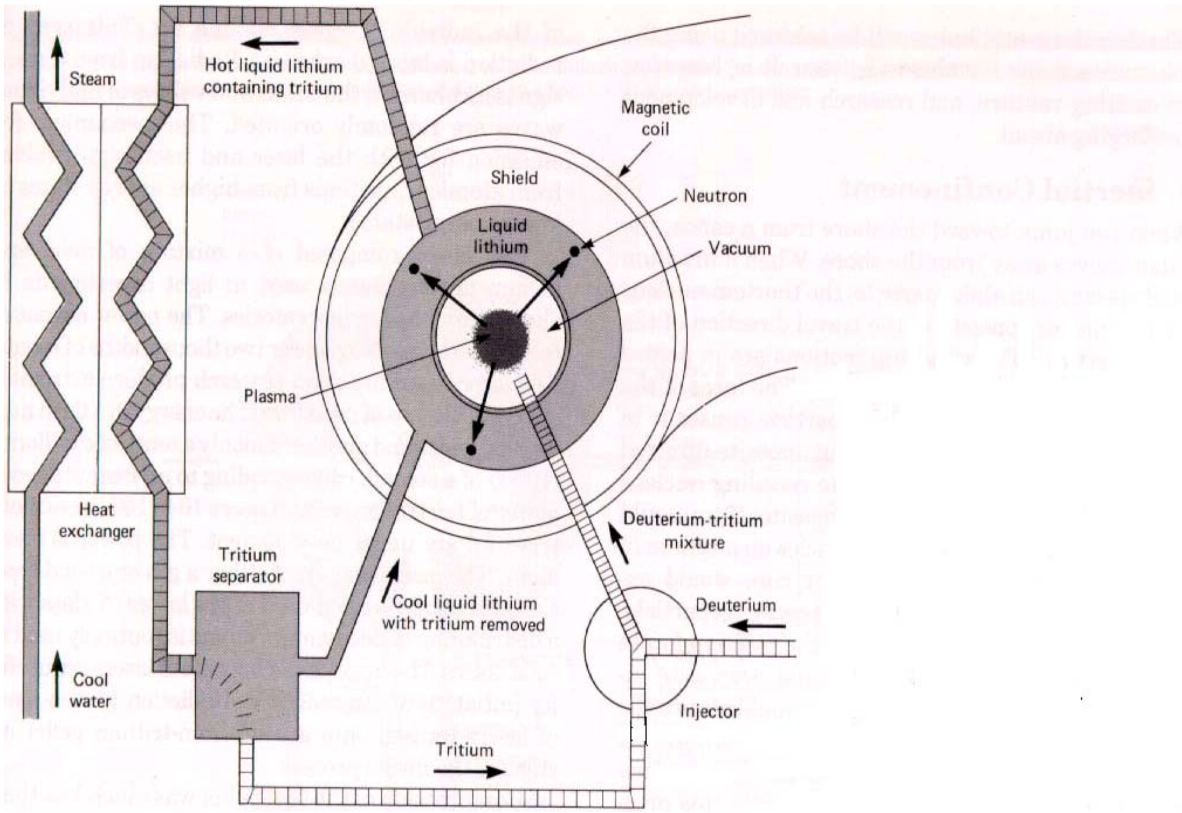


The Tokamak Confinement Geometry :



The reactor confines the hot and dense plasma of the fuel gas (deuterium) for a sufficiently long time in a donut or torus shaped device called Tokamak which makes the use of magnetic forces. “Tokamak” is an acronym derived from Russian words meaning “toroidal chamber and magnetic coil.” Current up to several million amps flows through the doughnut-shaped plasma made of deuterium and tritium. The Tokamak operates with a transformer action. The plasma constitutes the secondary winding of the transformer. The current in the primary produces a much larger current in the plasma, this current heats the plasma, producing the required initial temperature. Current in a coil surrounding the plasma produces a magnetic field that contains the plasma. Basically, the Tokamak magnetic field is a combination of a strong steady (for a time) toroidal field and a much weaker, pulsed poloidal field. In a purely toroidal magnetic field, the field lines are closed circles with different radii; as a consequence, the plasma drifts outward in the torus. By superimposing a weak poloidal field, the toroidal field lines acquire a slight twist so that they do not close on themselves. The twist in the field largely prevents the drift, and there is a marked increase in the plasma stability and the confinement time. The toroidal field component is produced by the electric current passing through coils which encirlces the torus in a vertical direction. The induction of the plama current for generating the poloidal field is done by appling a pulse of primary current to horizontal coils located within the central hole of the torus and around it. The increase and decrease of primary currents induce secondary currents within the torus, and these generate the desired poloidal magnetic fields.

Hypothesised Design of The Nuclear Reactor:



In the most likely scenario for development of a fusion power plant or a nuclear fusion reactor , a deuterium-tritium mixture is admitted to the evacuated reactor chamber and there ionized and heated to thermonuclear temperatures. The fuel is held away from the chamber walls by magnetic forces long enough for a useful number of reactions to take place. The charged helium nuclei which are formed give up energy of motion by colliding with newly injected cold fuel atoms which are then ionized and heated, thus sustaining the fusion reaction. The neutrons, having no charge, move in straight lines through the thin walls of the vacuum chamber with little loss of energy.

The neutrons and their 14 MeV of energy are absorbed in a "blanket" containing lithium which surrounds the fusion chamber. The neutrons' energy of motion is given up through many collisions with lithium nuclei, thus creating heat that is removed by a heat exchanger which conveys it to a conventional steam electric plant. The neutrons themselves ultimately enter into nuclear reactions with lithium to generate tritium which is separated and fed back into the reactor as a fuel.

The successful operation of a fusion power plant will require the use of materials resistant to energetic neutron bombardment, thermal stress and magnetic forces, and also there is a need for a steady state operation. To obtain a steady state, the magnet should be of super conducting type. They need to be specially designed to remain superconducting inspite of their proximity to the other ‘warm’ objects.

Another essential requirement for the net production of the nuclear fusion energy is that the break even condition be exceeded. This condition is that the plasma, be confined for the sufiicient time to permit the total recoverable fusion energy to balance the energy required to heat the plasma and to compensate for the radiation loss. The energy break even condition could be expressed in the terms of Lawson number which is the product of particle density and the confinement time in seconds. Thus when the fuel density is high, the rate of fuel burning is correspondingly more rapid, leading to a shortened required confinement time before the break even energy release is reached. For a commercially viable fusion process by D-T Plasma the value of Lawson number is $3*10^{14}$ second/cm^3.

Persisting Problems

Though a detailed design of the nuclear fusion reactor has been suggested but still the basic problems that still haunts the scientist studying the development of nuclear fusion reactors are of the attainment of the required extremely high temperatures, in the tune of millions of degrees Celsius such that the nuclei have sufficient energy to initiate fusion reaction and that of Controlability ie. the nuclear fusion reactions after being initiated should not go out of hand and a developed control mechanism should be necessarily present.

One solution to the high temperature problem would be the use of the soft X-rays which would give sufficient kinectic energy for fusion reaction. The bombardment of these specially developed rays would enable the achievement of high temperatures. Another solution for developing high temperatures would be in designing an apparatus which would use the nuclear fission reaction as a precurssor to the fusion, with the sole purpose of raising the temperature to the optimun temperature zone of fusion reaction. This would ineffect mean that we would use a fission reaction as a trigger to start the fusion reaction. For working of such a process the nuclear reactor design would have to have a separate chamber or furnace where fission would take place, from this chamber the heat generated should now be transported to the chamber having the nuclear fusion charge by the use of a suitable heat transporting medium.

Similarly, interlinked to this problem is that of controlling the reaction once started, since once the reaction is initiated subsequent reactions would be fuelled by the energy of the preceeding ones. Thus, after having brought the plasma to the ‘ignited state’ one must shut off the external energy source, continue to supply fuel to the reactor and somehow utilize the excess energy produced. Subsequently control can also be provided by controlling the plasma-wall interaction processes at the plasma boundary so that the plasma state duration is limited.

Another possible hypothesis suggested by scientists is to use a high-pressure jet to inject a noble gas (neon or argon) into the plasma,whose jet pressure effectively exceeds the plasma pressure, with the result that it penetrates to the central portion of the plasma within 1/1000th of a second, increasing the particle content of the plasma by a factor of above 50. As a result, the plasma energy is then dissipated uniformly in the form of ultraviolet radiation from the gas species, spreading the heat evenly over the wall area thereby also avoiding local hot spots. The plasma now cools quickly, leading to a rapid decay of the plasma current while minimizing wall currents and mechanical stresses. Thereby the loss or dissipation of energy ensures that the threshold energy for further fusion reactions is not attained, furthermore it is also effective in reducing greatly or eliminating the rapid multiplication of the plasma state fusionable charge (in effect causing a rapid decay of hydrogenic plasma). Besides if the energy dissipation is not uniformly spread but localised then the components inside the containment device are subject to damage due to wall surface melting by the hot plasma particles or because of high mechanical stresses developing from the currents flowing in the wall. But as highlighted, by injecting high pressure gas into the plasma the fusion reaction occuring in the plasma can be reliably terminated without any major deleterious effects.

Other than these problems stable operation at high pressure is crucial for a fusion plasma, because the power released from fusion reactions increases rapidly with the pressure. Unfortunately, as plasma pressure increases, the plasma itself can cause deformations of the magnetic field configuration, which very rapidly destroy the plasma confinement. A long-standing theoretical prediction has been that a perfectly conducting wall surrounding the plasma can improve its stability. It was also believed that when the plasma spins rapidly, an ordinary metallic wall should have the same stabilizing properties of a perfectly conducting wall. Scientist are now developing a new systems which could help in controlling the plasma to improve stability in two ways. The control system itself detects and opposes deformations of the plasma in much the same way that a superconducting wall would. The control system also automatically corrects small irregularities in the magnetic field, which would otherwise tend to have a “braking” effect on the rotation of the plasma. With the new control system, the plasma’s duration above the conventional pressure limit can be extended, and in some cases with rapid rotation the pressure can be increased stably up to levels almost twice as high as the conventional limit.

Another consideration that may pose a practical problem in the future is of superconducting magnets needed to generate the magnetic fields. Although superconducting magnets, closed by liquid Helium, have been built, they are smaller than those that will be required for fusion reactor. Presently, efforts are being made to develop such high intensity superconductors in research laboratories. The `Cable-In-Conduit' (CICC) superconductor is being specially made by Hitachi, Japan, and the magnets are being wound at BHEL, Bhopal.

Conclusion

The concept of nuclear fusion reactor holds large scale applicability. The fusion reactor will produce nuclear energy that can be easily transformed into electrical power, thus it provides an alternative to burning fossil fuels and will not produce green house gases that results in global warming. Once physically realised, the fusion reactor will convert nearly 90% of the energy it generates into electricity as compared to 40% for a traditionally coal-burning plant. It is postulated that 66 million KWh of energy will be liberated per Kilogram of Deuterium.

The reactor will cost half as much to run anually as coal-burning power plants as the fuel is cheap (as the main ingredients are Deuterium and Tritium which are abundantly available) and extreme safety measures are unnecessary as radioactivity is absent. Energy in the form of electricity and helium gas are the only products of the reactor. Hence it is safe and environmentally sound. The conversion process, of nuclear energy to electrical energy will be twice as efficient as thermal heat conversion, in which coal is burned to heat water and produce steam, which runs turbines that produce electrical power. Many coal-burning and nuclear fission power plants are built miles from cities because of their size and environmental dangers. The electricity is brought into cities by long, high-powered transmission lines, which results in the loss of almost half of the generated electric power because of electrical resistance in the wires and radiation given off through electromagnetic waves. With the fusion reactor, the lines can be eliminated since the reactor can be placed near or within cities of any size.

Besides, it is quite safe to use as the amount of fuel in the fusion system is very small. It is also inherently safe even on occasions of minor failure in the system.

It is because of the above potential advantages that much effort is being expanded in many countries in order to make fusion power a practical reality.

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