Nuclear Fusion Prospects as a Succeeding Energy Source -A Literature review

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ABSTRACT

In the present World scenario, one of the most significant 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

Although nuclear fusion is unlikely to be ready for commercial power generation in the coming decades, it remains nevertheless an attractive energy solution and arguably, the only truly sustainable option for large-scale baseload supply in the long-term. If the research and development in fusion energy deliver the advances predicted, then it will continue on a steady course to achieve this aim in the second half of this century. Fusion energy's many benefits include an essentially unlimited supply of cheap fuel, passive intrinsic safety and no production of CO2 or atmospheric pollutants. Compared to nuclear fission, it produces relatively short-lived radioactive products, with the half-lives of most radioisotopes contained in the waste being less than ten years, which means that within 100 years, the radioactivity of the materials will have diminished to insignificant levels. Fusion energy production has already been demonstrated by the European flagship experiment, the Joint European Torus (JET). The next step on the path to fusion energy is the international project International Thermonuclear Experimental Reactor (ITER), which is under construction at Cadarache (France). It aims to carry out its first experiments before the end of the decade and in the following years it should demonstrate the scientific and technical feasibility of fusion energy.

Europe is financing about 45% of the total construction cost, with one-fifth of this from France as the host state and four-fifths from the EU. The remainder is split between the other six participants (China, India, Japan, South Korea, Russia and USA). The E U Council has capped the EU contribution to ITER construction at EUR 6.6 billion24 for the period 2007-2020, including about EUR 600 million for associated costs. Most of the hardware is being supplied as in-kind contributions from the seven ITER Parties. Cash contributions from the Parties cover the ITER Organisation's running costs and some centralised hardware procurements. The successful operation of ITER is expected to lead to the go-ahead for the following step, a Demonstration Power Plant (DEMO), which would aim to demonstrate the commercial viability of fusion by delivering fusion power to the grid by 2050.

TECHNOLOGICAL STATE OF THE ART AND ANTICIPATED DEVELOPMENTS

Nuclear fusion occurs when the nuclei of atoms collide with one another and bind together. This releases large amounts of energy, which can be converted to heat and used to generate electricity as with other thermal power plants. The most efficient fusion reaction to use on earth is that between the hydrogen isotopes, deuterium (D) and tritium (T), which produces the highest energy at the 'lowest' (although still extremely high) temperature of the reacting fuels. For the fusion reaction to occur, the nuclei need to be brought very close together. If the atoms of a gas are heated, the motion of the electrons and the nuclei will increase until the (negatively charged) electrons have separated from the (positively charged) nuclei.

Figure 1: The ITER site in Cadarache (September 2011, preparatory work is well underway)
[Source: ITER/Altivue]

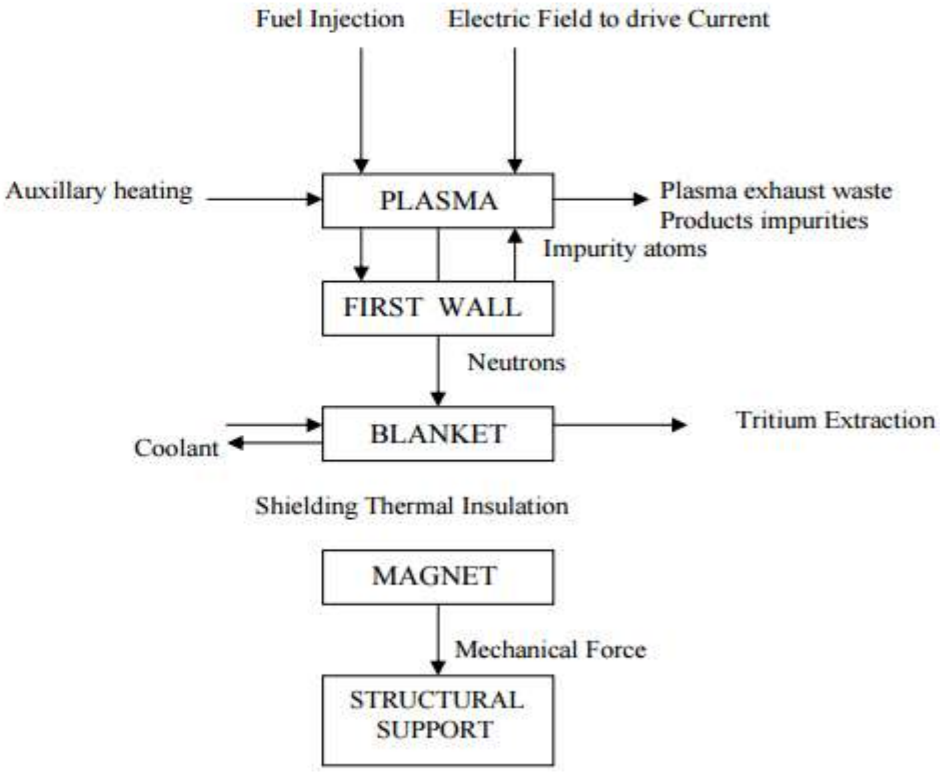
This state, where nuclei and electrons are no longer bound together, is called plasma. Heating the plasma further to temperatures in the range of 100-200 million °C, results in collisions between the nuclei being sufficiently energetic to overcome the repulsive force between them and to fuse. Experiments such as JET and ITER use the favoured “magnetic confinement” approach to fusion, in which strong magnetic fields confine the plasma - no solid material is able to confine a plasma at such high temperatures. The aim is that the plasma should maintain its high temperature over long periods from the heat generated by the fusion reactions. Producing and maintaining a plasma with the necessary high temperature and sufficiently high density, is a challenging problem, requiring for example “additional heating” systems which can inject very high power into the plasma. Results from existing experiments give confidence that this can be done successfully in ITER.

WORKING AND DESIGN

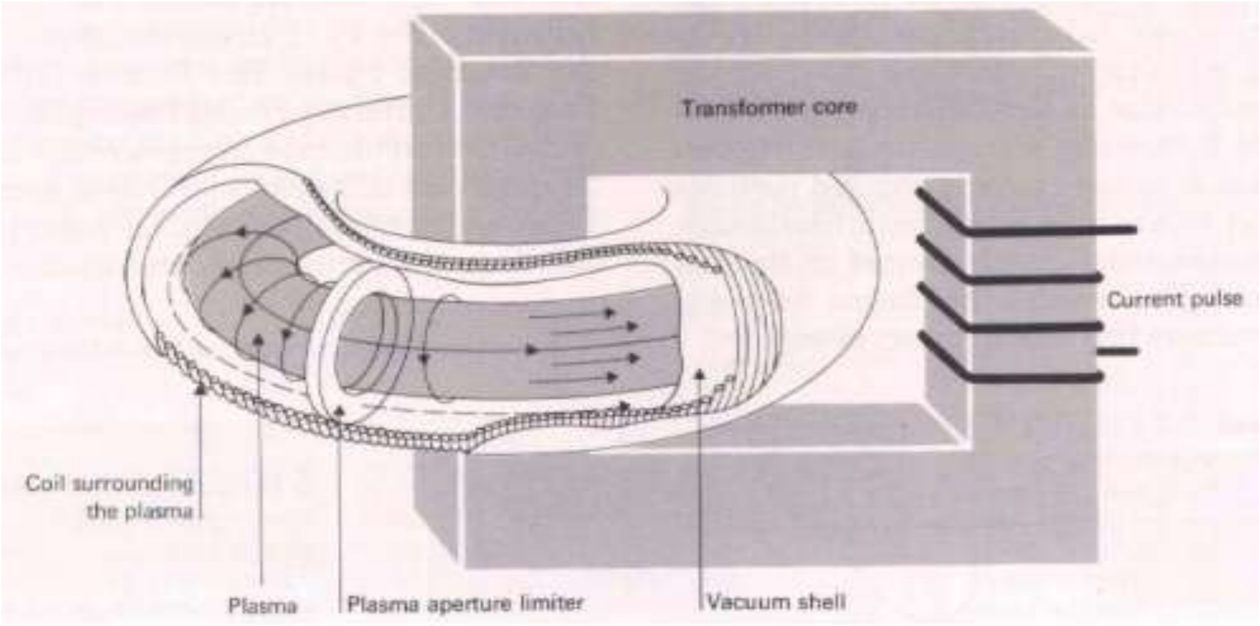
Significant research is on for the development of the nuclear reactor, one of the major projects most successful till date is the Steady State Superconducting Tokamak (SST-1) which is currently under fabrication at the Institute for Plasma Research (IPR), Bhat, Gandhinagar. For developing a nuclear reactor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

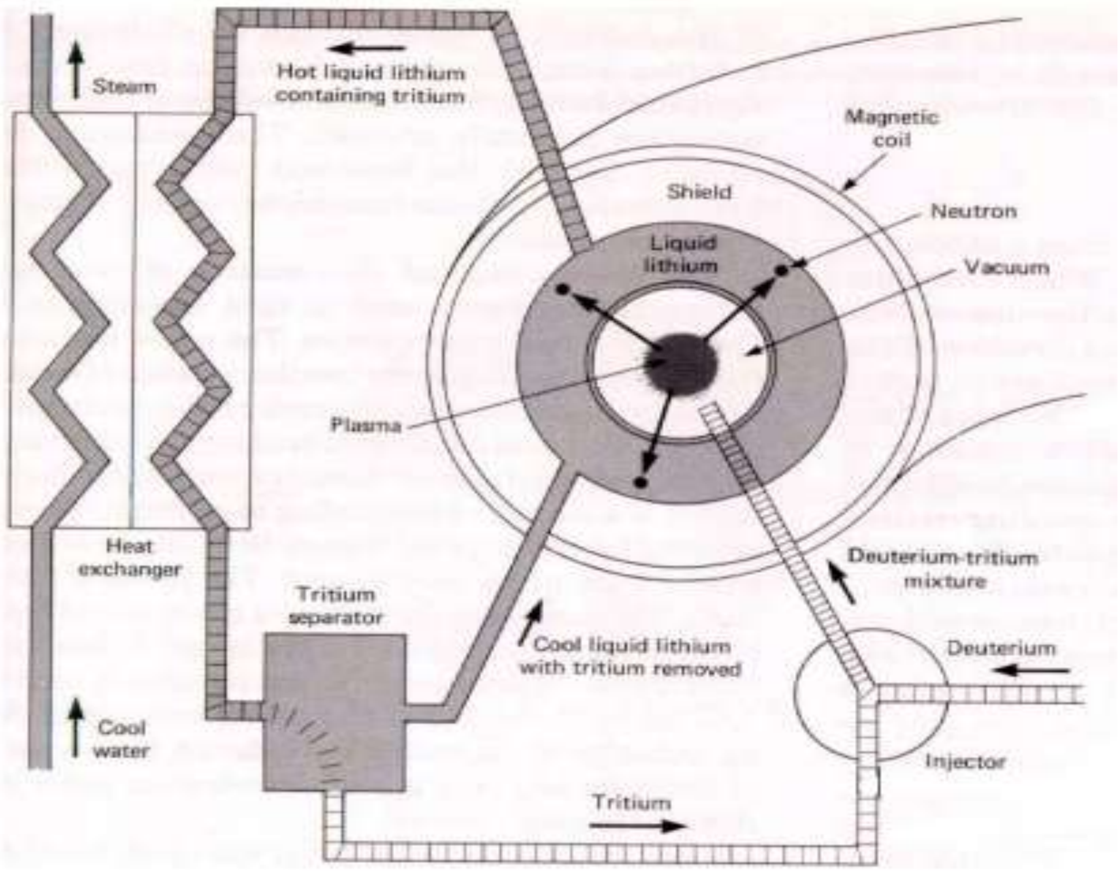


The Tokamak Confinement Geometry



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.

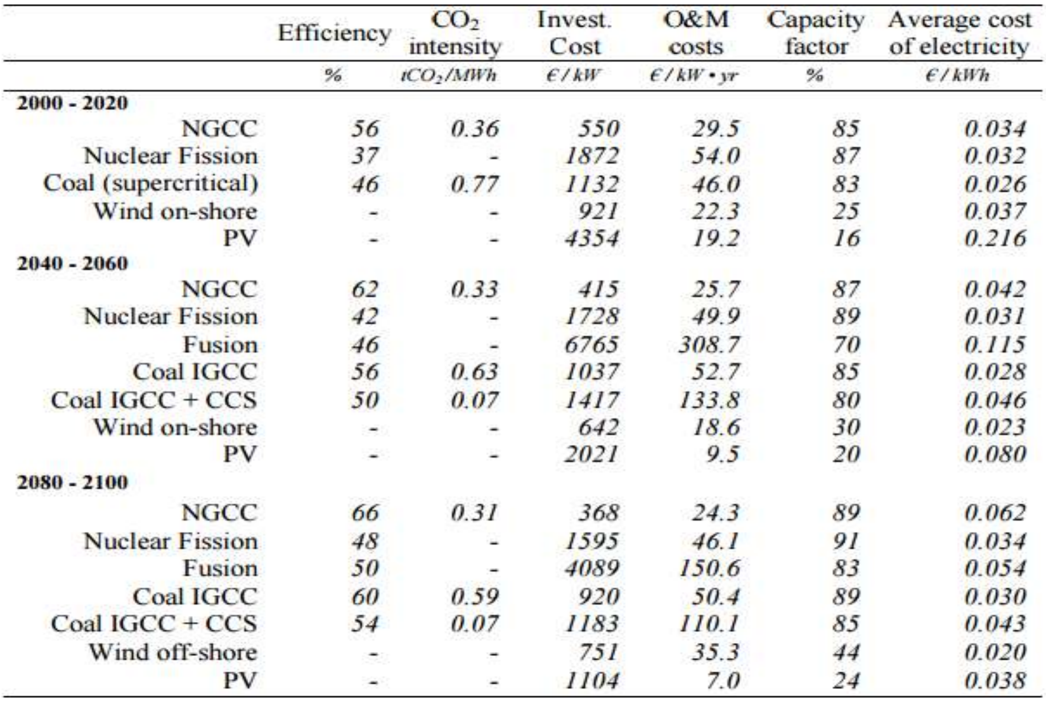
The neutrons, having no charge, move in straight lines through the thin walls of the vacuum chamber with little loss of energy. The neutrons and their 14 MeV of energy are absorbed in a "blanket" containing lithium which surrounds the fusion chamber. The neutrons' energy of motion is given up through 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*1014 second/cm^{3}.

TECHNOLOGY ASSUMPTIONS

In accordance with EURPROG data, the following main types of electricity generation technologies were distinguished among the existing power plants: Gas turbine (GT); Gas turbine operated in combined cycle (NGCC); Natural gas fired thermal power plant; Diesel engine; Fuel oil fired thermal power plant; Multifuel thermal power plant; Nuclear power plant; Hard coal fired thermal power plant; Lignite fired thermal power plant; Municipal wastes and biomass residues incinerator combined with steam turbine; Run-of-the-river hydro power plant; Reservoir accumulation hydro power plant; Pumping and storage hydro power plant; Wind power plant. Averaged values were defined to describe technical and economic performances of the power plants of existing technologies. Besides the existing technologies, the following main types of candidate power plants were considered: Oil gasification GT operated in combined cycle, Supercritical pulverised coal thermal power plant, Integrated coal gasification GT operated in combined cycle (IGCC), Lignite-fired fluidised bed combustion thermal power plant, IGCC with carbon capture and sequestration (IGCC+CCS), Integrated coal gasification fuel cell operated in combined cycle, Natural gas fuelled fuel cell, Photovoltaic (PV), Wind On / Off-shore. Detailed assumptions on main technical and economic parameters of selected candidate power plants are given in TABLE I. Average values of levelized electricity cost shown in last column do not include the costs related to electricity grid connection and grid extension.

Table I: Selected Numerical Assumptions on Techno-Economic, Parameters of Candidate Power Plants In Planelec-Pro Model



	Efficiency	CO_2 intensity	Invest. Cost	O&M costs	Capacity factor	Average cost of electricity
	%	tCO_2/MWh	€/kW	€/kW • yr	%	€/kWh
2000 - 2020						
NGCC	56	0.36	550	29.5	85	0.034
Nuclear Fission	37	-	1872	54.0	87	0.032
Coal (supercritical)	46	0.77	1132	46.0	83	0.026
Wind on-shore	-	-	921	22.3	25	0.037
PV	-	-	4354	19.2	16	0.216
2040 - 2060						
NGCC	62	0.33	415	25.7	87	0.042
Nuclear Fission	42	-	1728	49.9	89	0.031
Fusion	46	-	6765	308.7	70	0.115
Coal IGCC	56	0.63	1037	52.7	85	0.028
Coal IGCC + CCS	50	0.07	1417	133.8	80	0.046
Wind on-shore	-	-	642	18.6	30	0.023
PV	-	-	2021	9.5	20	0.080
2080 - 2100						
NGCC	66	0.31	368	24.3	89	0.062
Nuclear Fission	48	-	1595	46.1	91	0.034
Fusion	50	-	4089	150.6	83	0.054
Coal IGCC	60	0.59	920	50.4	89	0.030
Coal IGCC + CCS	54	0.07	1183	110.1	85	0.043
Wind off-shore	-	-	751	35.3	44	0.020
PV	-	-	1104	7.0	24	0.038

Source: Authors' estimation based on [9] – [16]

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 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. 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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