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Nuclear Fusion Reactor – A Review Study

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ABSTRACT

This paper aims to explode nuclear fusion reaction, the theory behind nuclear fusion reactors and countries with different types of fusion reactors along with their fusion theory involved. The energy generated from nuclear fusion reaction is much more huge as compared to nuclear fission reaction, so there have been many research going on this field to explode efficient way to extract this energy into electricity through fusion reactors. The advantages of nuclear fusion over fission is also been discussed and why do we need nuclear fusion energy. Nuclear fusion reactors are key to future energy.

KEYWORDS: *Future energy, MCT, ICF, Fusion reactor, Fission reaction, ITER, DEMO*

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INTRODUCTION

Nuclear fusion is a process of combination of two or more atomic nuclei to form a different atomic nuclei. Whereas nuclear fission is a process in which a larger atomic nuclei is made to split into smaller atomic nuclei. During both the processes a huge amount of energy is radiated, this energy is used to generate electricity. The nuclear reaction are carried in a special environment called nuclear reactor. These nuclear reactors should be properly build to carry the reaction with transfer of energy and without harming the outer environment. Nuclear fusion is the same process which happens or powers the sun and the stars, and also referred as the ultimate energy source for the future of humankind. Nuclear fusion promises clean and safe energy, while a small amount of fuel generates a huge amount of energy. There is an international organization for development and research on fusion reactors named ITER (INTERNATIONAL THERMOUCLEAR EXPERIMENTAL REACTOR). Many countries are investing a huge amount of money on research and development over fusion reactors. Fusion was observed much earlier than fission. Scientists named Oliphant, Harteck and Rutherford were experimenting with deuterium ions, which they bombarded deuterium ions with target compound containing deuterium, they found that a new isotope of hydrogen and a neutron was produced. This gave a path way for further research on fusion processes and reactions.

Fundamentals of Nuclear fusion science

In fusion of two or more light atomic nuclei, the mass of the product side product slightly less than the sum of the reactants. This difference in mass is the conversion of mass into energy, as was theorized by Albert Einstein, and later proven.

$E = (\text{delta})\ mc^2$

Where E is energy generated
Delta is change
m is mass
c is speed of light

So the fuel in fusion reactors are hydrogen isotope i.e. ^2D and ^3T. The fusion reaction is given below:

$$^2D + {}^3T \rightarrow {}^4He\ (3.52\ MeV) + {}^1n\ (14.06\ MeV)$$

When deuterium is bombarded with tritium in specified conditions then they combine to form a bigger nuclei that of Helium atom and releasing 14.06 MeV of energy which is used for generation of electricity. Combining these small atoms are not so easy as they need to overcome a large force of repulsion, so the specific condition needed are very high pressure and temperature.

Approach to Fusion Reactor

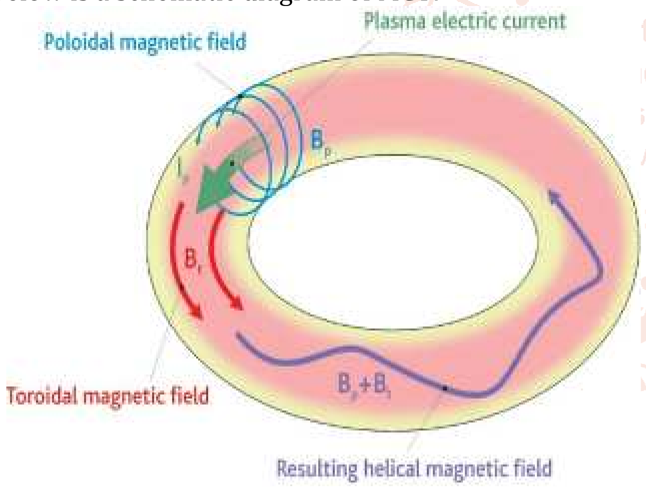
There were many theories came up for the approach to fusion reactors for the combination of two atoms, though many theories were there out of which the two prominent theory which enlightened most of the scientists and researchers were – magnetic confinement and inertial confinement.

1. Magnetic Confinement Theory (MCT):

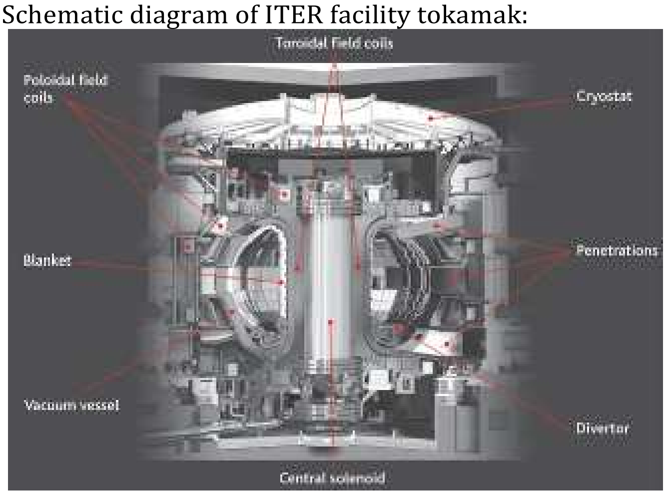
Magnetic confinement fusion reactors are the most powerful approach which makes use of magnetic fields which are generated from electromagnetic coils which is to confine the fusion plasma in a toroidal shaped vessel. In 1965, experiments were made by Soviet Union on fusion reaction and fusion reaction devise, they ended up making a toroidal chamber like with axial magnetic field which they named as Tokamak, it's a donut-shaped vessel that were designed to fulfill the purpose for confining high temperature plasma using cross magnetic field. After this many countries tried working on this theory and tried exploring them and also advancing the theory more in efficient way. After the cold war was over, many countries came up for collaboration towards the development of fusion reactors. Together countries like India, European Union, Japan, Russia, US, South Korea and China came up for the development and ended up formation of ITER which will make effort to build the tokamak reactor.

Magnetic confinement pf plasma is produced by two fields Toroidal magnetic field generated by toroidal fields and Poloidal magnetic field generated by electric current due to the movement of ions in plasma state. So the interaction of these fields result in formation of helical shaped magnetic field which contains our fuel i.e. deuterium and tritium, for their combination the container is a sealed toroidal shaped vessel naming vacuum vessel. These helical field energies the kinetic energy of the hydrogen isotopes, thus the bombardment will be much more effective and thus we will get the desired results.

Below is a schematic diagram of MCT:



Schematic diagram of ITER facility tokamak:

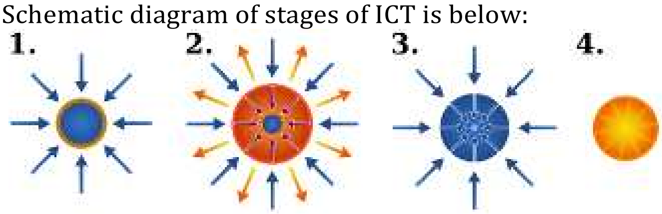


In the above tokamak fusion reactor we can see the blanket which is toroidal shaped containing vacuum vessel where fuel are introduced, the diverter which is kept to suck the alpha particle produced in the fusion reaction taking place when the fusion reaction happens.

2. Inertial Confinement Theory (ICT):

A. Unlike the MCT, inertial confinement theory attempts to make externally heat and compress fusion fuel resulting in achieving a very high temperature even though very high densities required for the initiation of the nuclear fusion reaction. Most of the fusion reactor which use the concept of ICT, they use high density and high power Laser to compress and generate high amount of heat for the fuel.

Schematic diagram of stages of ICT is below:

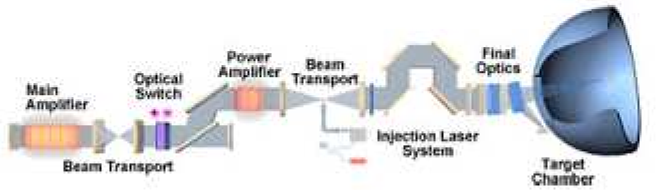


Here the blue arrows indicate radiation; orange shows blowing off; purple shows inwardly transmitted thermal energy.

Laser beams produces X-rays which rapidly heats the surface of fusion target and thus forming a plasma envelope surrounding it. Fuel is then compressed by the blow off of the hot surface material. Then in the final part of capsule implosion, the core of the fuel reaches 20 times the density that of lead and then ignites at 100,000,000 °C.

Now the thermonuclear burn which spreads rapidly through the compresses fuel, yielding much more energy that the input energy.

Below is a modeled diagram of ICT:



From the above diagram it is clear how the main amplifier and the power amplifier help in boosting the Laser beam to hit the fusion target and bring them in plasma state.

Design of Fusion Facility

In nuclear fusion reactor, the tokamak building is the main part which is surrounded by rooms which are used for cooling the systems and the vacuum vessel relief tank. The tokamak building comprises of vacuum vessel which introduces the fuels and diverters which help to remove the fusion product. The building around the vacuum vessel helps to keep the components located around them cool and extract the removal of waste or recycling back into vessel. All the nuclear building have ventilation system which provides confinement of radioactive substance.

The natural availability of tritium is very difficult so there is chamber for tritium breeding, then the tritium generated from here is sent into the vacuum vessel. The most prominent method of extracting tritium is when bombarding lithium-6 with neutron:

$$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{3}_{1}H + 4.8MeV$$

There are two types of tritium breeding blanket which are under construction:

Helium Cooled Ceramic Breeder (HCCB), which uses lithium based oxide ceramic for the purpose of tritium production, here beryllium is used as a neutron booster and helium is chosen to cool the structure.

Dual Coolant Lithium Lead (DCLL), which uses LiPb eutectic for the generation of tritium, as a neutron booster and for cooling the structures, helium is also used for cooling.

The main characteristic of ITER facility tokamak are: a vacuum vessel with volume capacity of approx. 1600 m^3; A nominal plasma current producing of 15 MA; a beryllium layer is used for the first wall for the blanket; tungsten is used for the first wall for the diverter; there are several modules build for tritium breeding and also developing more methods for tritium breeding to come.

Nuclear Fusion Reactor Projects

Different countries have come up with different approach towards the development of their own fusion reactor, however, there is been two general strategies that have been seen in many countries reactor project, these are-

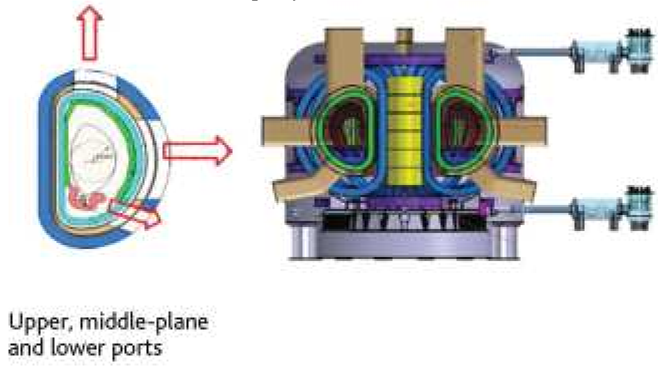
1. Before making a fusion reactor, some countries aim to demonstrate the feasibility of the reactor by building small experimental reactors which fusion power lies below 1000 MW; many countries including China, USA and India follow this idea for the building a proper and efficient reactor which can deliver a better output power in future.
2. And there are some countries which directly aims to build fusion reactors for the power generation, with a power output aiming above 1000 MW; countries like Republic of Korea, European Atomic Energy Community and Japan are working on these projects.

China's "CFETR" project

People's Republic of China consider many factor and fact before building fusion reactor. Chinese project target the tritium breeding blanket optimisation and their behaviour, they also seek the materials required for the vacuum blanket, the resistance of material used which come in contact with high neutron flux and to optimise the design of the diverters along with trying to increase the fusion output power up to 1000 MW.

The project is named as China Fusion Engineering Test Reactor (CFETR). Operation of this reactor is likely to start up with a fusion power output of 200 MW, which can be raised up to 1000 MW in further advancement of the reactor. The tritium breeding blanket to be used has not yet been chosen, here the tokamak i.e. the MCT configuration is used with middle-plane, lower and upper penetration of vacuum vessel in which a large sector is made of blanket and diverter so that it could be helpful at the time of maintenance.

Below is the Chinese project reactor model:

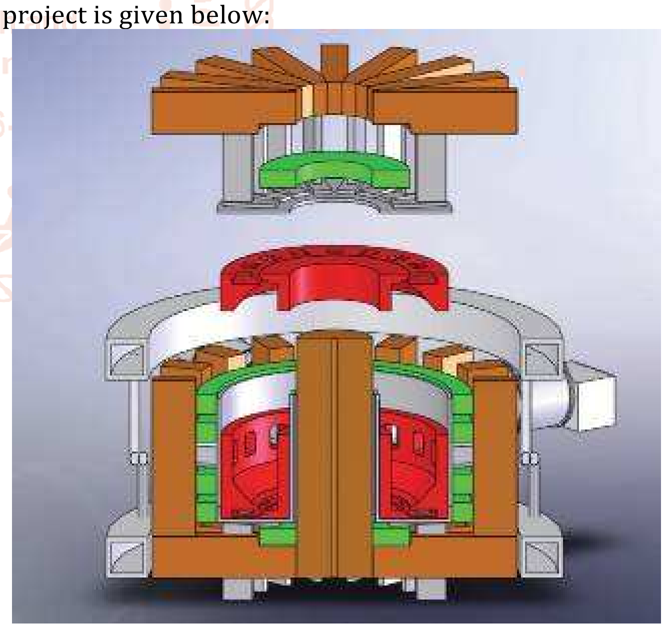


America's "FNSF-AT" Project

There has been a proposal by the department of Energy of America which suggests to build an experimental reactor first so that they can test all the possibilities and then implement, they named this project as Fusion Nuclear Science Facility Advanced Tokamak (FNSF-AT).

This project aims towards the development of a system which will produce self-sufficient in tritium breeding which also allow electrical power generation. Optimisation of service life of vacuum vessel and the components related to it. They have provided a vertical penetrations for the purpose of maintenance. The plan of this reactor is to produce a fusion output power of 125 MW and at commissioning this can be raised up to 250 MW. The proper commissioning of this reactor will take time and therefore not conceivable before 2050.

The experimental modelled design of FNST-AT reactor project is given below:



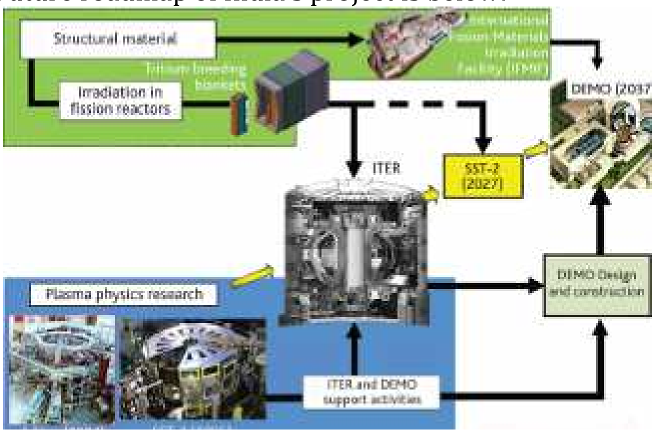
India's "SST-2" Project

The aim of the project is to study various type of tritium breeding blanket, components involved for the output power to be raised upto 500 MW.

The project is named as Steady State Superconducting Tokamak-2 which can be finished with the reactor construction by 2027 and India is aiming for a power reactor with a output power if 3300 MW by 2037.

The main idea behind SST-2 is to test the equipment for future power reactor which can be huge power house itself. The operation of this experimental reactor will start with a fusion output power of 100 MW, then it could be raised upto 500MW in later operation.

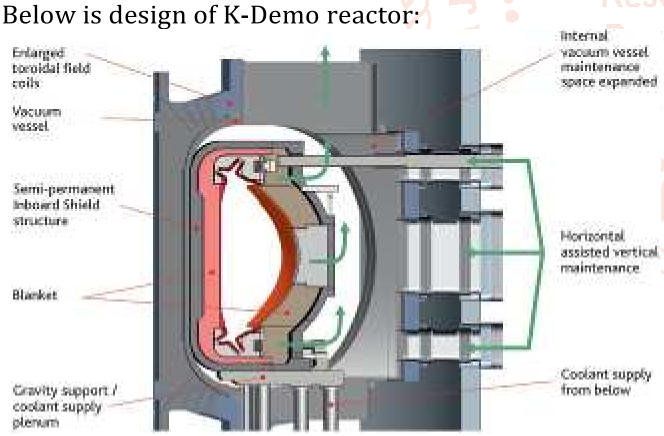
Future roadmap of India's project is below:



South Korea's "K-DEMO' Project

South Korea's project is similar to those of the ITER, this reactor is estimated to avail atleast 70% for the fusion output power for generation of electricity, and here also vertical penetration is given for maintenance. The reactor will be incorporated in two phases; in phase one its output power will be limited to 10% of maximum capacity; in second phase the output will be increased to 70% for generation purpose. Here water cooled ceramic breeder (WCCB) tritium breeding is to be used with lithium–based Oxide ceramic for the production of tritium, here beryllium is used as a neutron booster and pressurised water for cooling.

Below is design of K-Demo reactor:

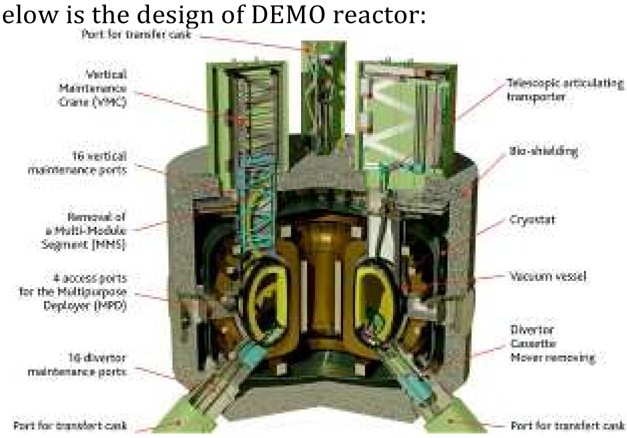


Europe's "DEMO" Project

The project aim to build a reactor similar size to ITER, which is expected to product an output power of 500 MW of electrical power with good availability for fusion power output of 1950 MW. Here also vertical penetration is preferred for maintenance and tritium breeding has not be decided.

This project aims to demonstrate the reactor around 2040. This reactor is also based on tokamak configuration. DEMO has the highest number of diverters for maintenance purpose and has an extra segment named MMS for removal of waste products.

Below is the design of DEMO reactor:



Japan's Project

The Japanese project has an aim to make DEMO reactor which gives fusion output power of about 1000 MW. National Institute for Fusion Science (NIFS) and Japan Atomic Energy Agency (JAEA), this collaboration foresees construction of the fusion reactor in around 2030.

Comparison between Fusion Reactor Projects

We have compared different countries nuclear fusion reactor on basis of year of completion, output power, cooling system and technology.

COUNTRY	YEAR OF COMPLETION*	OUTPUT POWER *	COOLING SYSTEM	TECHNOLOGY
China's "CFETR"	2030	200 MW	COLD WATER	MCF without vertical penetration
America's "FNSF-AT"	2030 - 2050	250 MW	Liquid Helium	MCF with vertical penetration
India's "SST-2"	2037	100 MW	NO DATA TILL DATE	MCF
South Korea's "K-DEMO"	2037	300 MW	Pressurised Water	MCF with vertical penetration
Europe's "DEMO"	2040	500 MW	Pressurised Water	MCF with vertical penetration

From the above comparison we can see that in coming years almost country will have this ultimate energy source. Also from the comparison we can see that South Korea's K-DEMO reactor is a powerful one which is similar to that of ITER. Also most of the countries prefer to make use of magnetic confinement fusion method along with vertical penetration for maintenance.

Why most of fusion reactors use MCF technology?

The answer for this question is that many fusion reactors use magnetic fields to accelerate the movement of hydrogen isotopes and thus the impact of the collision is high and more chances of fusion may happen, but when we compare this technique with other, there is no need for Laser for high temperature. Also generating high temperature like in ICF technique will require a good strong vessel blanket to withstand the high temperature.

Why Nuclear Fusion Over Fission?

1. Its being a quite common question why we need to move towards fusion when we already have fission reactors, we know that nuclear fusion reaction generates much more energy than fission reaction i.e. for the same amount of fuel used.

2. Nuclear fission reactions generate chain reactions and hence if not controlled properly its unsafe. But this is not in case of fusion reaction as they cannot go into chain reaction as the specific condition is very difficult to get for their continuous bombardment.
3. Waste disposal of used nuclear fission reactor fuel is also an indeed problem as they are harmful for environment if not disposed properly as they continue to be harmful by radiation. But this is not in case of fusion reaction as the product alpha particle captured is used is for other purposes.
4. In nuclear fission reactors any sort of contamination will lead to exploding of the reactor but this is not in case of fusion reactors as it is difficult enough to reach and maintain the precise conditions necessary for fusion—if any disturbance occurs, the reaction stops.
5. Fuel extraction is also a great factor in fission reaction as U^{235} is not available everywhere but in fusion reaction tritium breeding helps to produce one fuel and similarly deuterium is also extracted from some reaction.

Also any many new technologies are yet to discover and to come which will make the fusion reactor more powerful.

Conclusion

In coming years, the ultimate source of energy is Nuclear fusion energy, the process which powers the sun and the stars, though this only we can imagine the amount of energy that can be released and with that make use for generation of electricity.

The result of this review study highlights the current theories for nuclear fusion reactors and the ongoing projects on fusion reactors, their current plans for the development of fusion to deliver the promise of sustainable and clean energy. This paper have also compared between different countries reactor project and their future goals to achieve this energy resource.

Now, seeing the current situation, we could believe that in near future fusion energy will be reality. Every country is making effort to make efficient reactors for enhancement of fusion energy into commercial usage.

The burden on other sources of energy will be reduced as there is a shortage of conventional sources. Though a huge amount of investment is required but once this is established the production and running cost is very low as compared. Both nuclear fission and fusion are the key to future energy source.

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