TOKAMAK DESIGN, ITS IMPLEMENTATION IN THE ITER REACTOR, AND THE FUTURE OF NUCLEAR ENERGY

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Abstract

Our research was in the Tokamak design, the International Tokamak Experimental Reactor currently being constructed in France, and the future of nuclear energy. The ITER project is set to be completed in December 2025. Tokamak Reactors are a type of nuclear fusion reactor that utilizes magnets in conjunction with a deuterium-tritium reaction to create energy. The magnets allow the plasma from the reaction to form a toroid shape, causing the helium nucleus that is created to remain in the magnetic field created by the magnets in plasma form, and the neutrons produced by the reaction to hit the "blanket" of the reactor, which is made of lithium. The neutron then theoretically allows for the Tritium-cycle to occur. The plasma contained by the magnets, as well as the energy generated by the lithium decay results in energy output. The ITER reactor is significant because it is theoretically capable of multiplying the power input by ten, from fifty to five hundred MW of power. The process, if completed successfully, would create a near infinite source of energy for the planet, dramatically reducing the need for fossil fuels and contributing to ending their contribution to global warming. It also leaves behind very little nuclear waste and has no risk of meltdown. Sustainability is also a large topic of discussion when it comes to the ITER with a lot of the project being very sustainable and part of it not being sustainable.

History of Nuclear Fusion

1930- Fusion was discovered by scientists observing how the sun ran
1950- Fusion reactors were up and running in the Soviet Union, United Kingdom, and United States
Late 1950s- The idea of a Tokamak reactor was developed in the Soviet Union
1970- The United States focuses all of its fusion research on the Tokamak
1990- International collaboration with Tokamak reactors began with the Tokamak Fusion Test Reactor in the U.S. and the Joint European Torus (JET) in the UK
1991- The Joint European Torus achieved the first controlled release of fusion power
2007- ITER was founded as an organization
2010- Construction on thee ITER began

ITER Under Construction

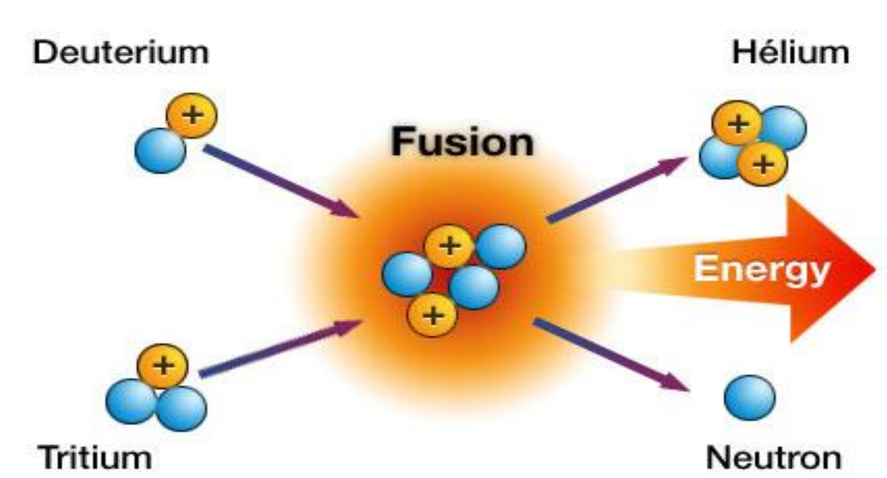
Physics of the Tokamak

Thus far during preliminary research stages, certain constraints are set upon the theoretical reactor to limit variance of the result and remain scientifically possible. These constraints apply to the maximum magnetic field, stress, maximum current density, and current density of the winding pack. Doing so allows for physics to solve for the remainder of the necessary data in the Tokamak reactor. Using two separate differential equations relating energy to the path slowed of the released neutron in the reaction and neutron flux to the path reaching Tritium fission required, the thickness of the blanket can be found using the equation $\Delta x = \lambda_s * \ln(1 + \alpha_B * \ln\left(\frac{\Gamma_0}{\Gamma_b}\right))$. From the blanket, both the major and minor axes of the toroid can be found. This allows for the calculation of the magnetic field at the center of the toroid such that it is not higher than the initial constraint. Next, the structural thickness must be found on the magnets, which can be derived from Newton's Second Law relating the magnetic forces applied the standard formula for centripetal force due to a stress. The last stage of the derivation process requires the finding of the current travelling through the central superconductor to generate the primary magnetic field. By using pressure, temperature, and plasma density, the current can be found using ELMy H-Modes, a relation between plasma processes that allows for high-energy confinement. Using these findings from the theoretical plasma research that has been completed, the appropriate values can be found for the preferred method of operation of the system.

What Fuels the Tokamak?

The reaction itself located inside the toroid is a Deuterium-Tritium reaction. This reaction can be modeled by the equation: $H_1^2 + H_1^3 \rightarrow He_2^4 + n_0^1 + 17.59\ MeV$. This equation shows the combination of Deuterium and Tritium that releases a Helium nucleus, a free neutron, and 17.59 MeV of energy. The Helium nucleus remains inside the plasma toroid, the neutron collides with the blanket, and the free energy is collected via divertor and converted to usable power. The major issue faced with the Deuterium-Tritium issue is overcome via use of a properly adjusted blanket. This issue is caused by the rarity and relatively short half-life or Tritium (12.3 years) preventing stockpiling. Using a Beryllium Blanket, a second nuclear reaction can take place, this time via fission instead of fusion. Using the equation: $n + Li_3^6 \rightarrow H_1^3 + He_2^4$, Lithium is fused with the free neutron to create another Helium nucleus and excess Tritium, which can be harvested off the blanket for further use.

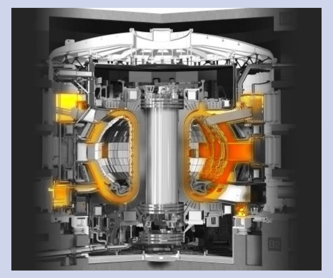
Deuterium-Tritium Fusion



Components of ITER

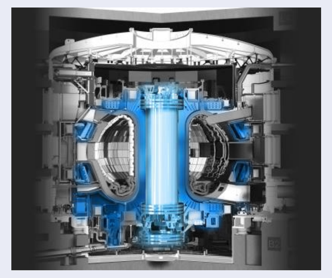
Vacuum Vessel

The vacuum vessel is a toroid with a volume of 1400 m^3. Its functions include creating a high vacuum environment to keep the plasma pure, acting as a nuclear shield for safety, and it supports the components housed in the wall of it.



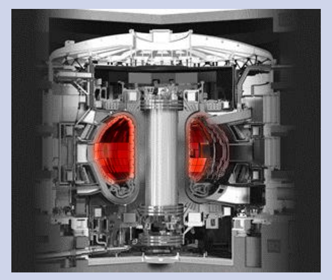
Magnets

The magnets, made out of niobium-tin, are located in the center of the toroid and along the walls of the vacuum vessel. Their main function is to keep the plasma from touching an melting the vacuum vessel.



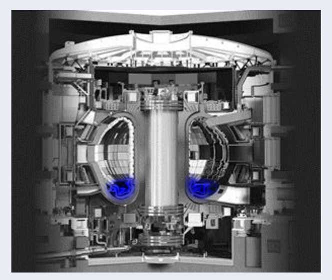
Blanket

The blanket is the structure covering the walls of the vacuum vessel. The main function of the blanket is to slow down the high energy neutrons and convert the kinetic energy of the neutrons into electricity.



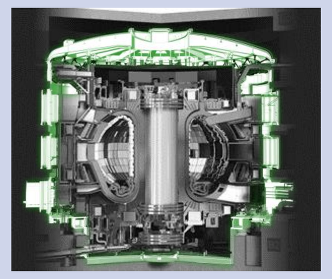
Diverter

The diverter is located at the bottom of the toroid. Its main functions are to collect and remove impurities from the plasma and extracting heat from the plasma to maximize the power obtained from the reaction.



Cryostat

The cryostat is the outer shell of the reactor that has a volume of 16,000 m^3. Its main function is to create an ultra cool environment for the reactor while also giving easy access for maintenance.



Sustainability of ITER

One of the most accepted definitions of sustainability is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The ITER has some aspects that agree with this definition and some aspects that go against this definition. The ITER has the ability to meet the needs of future generations. If it operates how it is set to and if it is able to be produce power commercially, there will be enough fuel for this reactor to produce clean power for close to a billions years. On the other hand, the ITER does not meet any needs of the present and it has a very unsustainable cost currently. The ITER has yet to begin even producing fusion plasma to create power and meet any current requirement in the power industry. In addition to that, countries are having trouble sustaining the cost of the reactor as it is now approaching $22 billion dollars for the total cost of the reactor.