Thermonuclear fusion research progress and the possibility to commercialize fusion powered electricity

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***Abstract*- This paper reviews the technical and physical requirements needed for the production of electricity from nuclear fusion energy. Multiple improvements in the understanding and possible utilizations of the nuclear fusion are presented. The most recent knowledge and solutions to solve the problem of containing and igniting a fusion reaction are compared and explained. The goal of this paper and thus the main element of comparison is to study the production at a competitive cost of electricity from the power released by a nuclear fusion. We focus on three problems blocking the way to achieving this goal. We examine the development of adapted materials for the confinement of the extreme condition leading to a nuclear fusion and compare the three different solutions that are nowadays the closest to reaching our goal. Our second point is to study the way to transform fusion energy into electricity adapted to the different projects mentioned previously. Finally, we compare the projects on an economic and technologic scale to have an idea of their feasibility and the possible date of their first energy production.**

***Keywords*- utilization of nuclear fusion, cost of electricity, fusion reaction, thermonuclear reactor**

I. INTRODUCTION

In 2016, 90% of the US electricity production came from non-renewable or nuclear energies (should be called nuclear fission energy). The burning of enormous amounts of coal, petroleum, and natural gases badly affected the environment and lead to the exhaustion of resources. The nuclear energy production by using the fission of an atom of uranium products of course heat but also dangerous radiation and leave behind radioactive elements. Since the industrial revolution in the middle of the nineteenth century and more recently with the realization on the dramatic heat up and climate change of our planet, the ultimate goal of the human species would be to have an unlimited access to a non-polluting source of energy. In this perspective, fusion energy would revolutionize our way of consuming and using energy. The cost of energy would dramatically drop because the main fuel for a nuclear fusion reaction is abundant on earth's surface and requires no excavation nor prospection at all. A nuclear fusion reaction is the assembly of two very light elements, two hydrogen isotopes named deuterium (^2H) and tritium (^3H). Under high temperature and pressure conditions, those two isotopes merge and the fusion reaction results in an enormous emission of heat as well as an atom of Helium (^4He) and a neutron. The helium nucleus has a slightly smaller mass than the sum of the masses of the two hydrogen nuclei, and the difference in mass is released as kinetic energy according to Albert Einstein's famous formula $E=mc^2$. The energy is converted to heat as the helium nucleus, also called an alpha particle, and the extra neutrons interact with the material around them.

Nowadays, three different design to produce the condition allowing the exploitation of a nuclear fusion reaction have emerged. First, the magnetic confinement, major branch of development in the discipline, which consists in using the electrical potential of the plasma present in the reaction chamber to repeal thanks to magnets all of the reactive in the middle of the chamber, hence rising up the pressure and temperature of the mixture. The second solution would be the inertial confinement consisting of mixing the deuterium and tritium mixture in a small tank, usually the size of a pellet and then bombard it with very powerful lasers to get the pressure and temperature go up. Finally, the electrical confinement which uses the very good electric conductivity of the plasma to send a strong current into the mixture, contracting it and rising the temperature and pressure.

All those projects are still in the elaboration process and none of those actually succeeded in producing more energy than the basic input needed. Since the middle of the nineteenth century, billions of dollars have been invested but no results have come out yet and the finance is a variable impacting all the projects. The access to resources vastly determine why we still don't have no fusion powered electricity in our homes.

II. BACKGROUND

The discovery of the fusion and discussion about its exploitation started at the same time as the fission program. The first major advances realized in the fusion energy control were military. A fusion reaction can be initiated by good chemical explosives, associated with other fissile element, the fusion reaction can create a chain reaction if it isn't contained. This is the concept of the Hydrogen bomb opposed to the atomic bomb which is made primarily from heavy fissile elements. The chain reaction of the Hydrogen bomb could be interesting if we could contain the energy released because then we could keep the plasma at a very high temperature and pressure without any input of heat nor work.

If we want to create any electricity from a fusion reaction, we have contain the energy released and most importantly if we want the electricity to be commercialized one day, keep the reactor running on a unlimited period. We can keep on running a reaction using basic physics of nuclear science. In the nature, deuterium (also known as heavy hydrogen) can be found very easily, however, tritium in a natural state is very rare on earth. As seen previously, the fusion reaction leads to the conversion of tritium and deuterium in a Helium atom and a neutron. This leftover neutron can be reused and when it merges with a Lithium (^{6}Li) atom it gives a new tritium nuclei which can be reused in the first process as well as an Helium atom.

The result of this reaction is a huge production of heat like a fission reaction and then we have to transform this heat energy into electricity. Adapting the technologies from the nuclear fission reactors to the fusion reactors should be pretty easy as it works on the same principle as most of our energy sources, creating work from heat. Regarding the second law of thermodynamics, work can create heat but not the opposite. We have to use a heat engine. This will most likely be a closed circuit of water going through the reactor, heated up until it become a superheated vapour which then goes through a turbine, making the blades rotate along an axis connected to a generator producing electricity from the work.

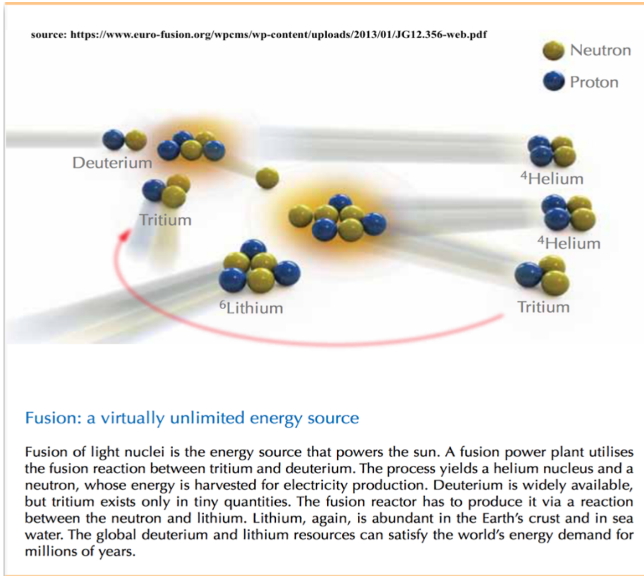


Figure 1 Fusion: a virtually unlimited energy sources

III. DISCUSSION

The three possible designs for a nuclear fusion reactor are compared based on their technical features, method of operation and cost.

A. Development of an adapted and efficient confinement method

A Tokamak is the most common form of magnetic confinement, it consist of a toroidal vacuum chamber (donut-shaped) made from super powerful magnets. In a Tokamak, plasma particles are confined and shaped by magnetic field lines that combine to act like an invisible path.

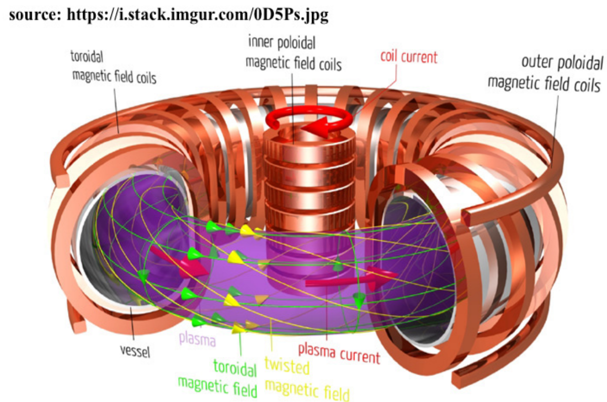


Figure 2 Representation of a Tokamak

For a fusion reaction to happen, the plasma inside of the Tokamak has to be heated up to 20 times the temperature at the core of the sun, up to 150 000 000 °C. Hence the plasma flux should never enter in contact with the chamber's walls. Some Tokamak around the world worked but none of them was able to give more energy out of the reaction than the initial input. However, the scientific community as a whole has agreed to put their forces together in the development of a new generation of reactor, bigger and profitable. This new project is called ITER (International Thermonuclear Experimental Reactor) supposed to be achieved by 2020 but is only the first step toward electricity production which will come in a second time with the project DEMO (DEMOnstration power plant), a post ITER project able to collect the heat exhaust from the reactor and send it to a power plant [1].

The inertial confinement fusion, our second design, works thanks to the enormous concentration of power of Lasers. In this case, a small capsule containing doses of hydrogen isotopes is put at rest and then bombarded with Lasers. The "direct drive" approach consists in concentring the full power of the lasers beams on the capsule heating it very fast and literally exploding the small capsule which explodes in all the directions. Then, as Newton said, “For every action, there is an equal and opposite reaction”. So as the capsule explodes, the elements at the center get compressed at a very high level permitting the fusion reaction to happen [2]. Another way of performing this experiment is to send the laser beams on the sides of the tank where the small capsule is contained and when the heated plasma in the tank hits the surface of the small capsule, it will make it explode in the same way as a direct drive reaction. This reaction is called indirect drive and is related beneath.

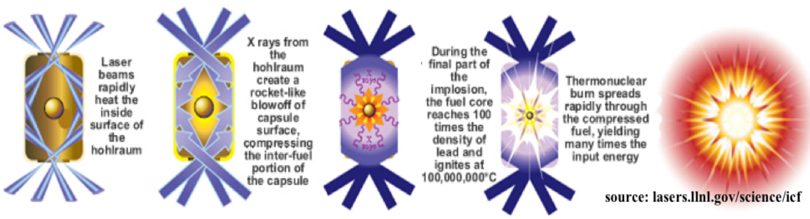


Figure 3 : Indirect drive inertial fusion confinement

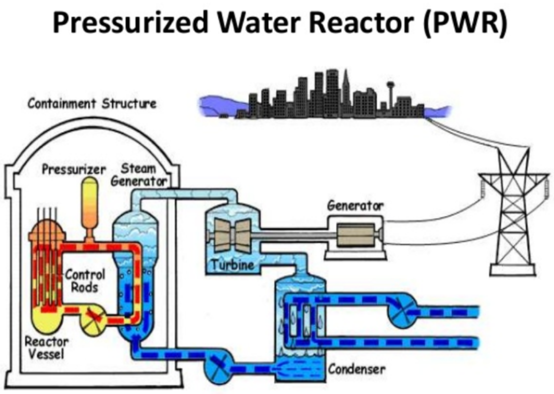
The electrical confinement, our last design, is a mix between our first two designs. It consist in using the very good conductivity of plasma to create the conditions leading to a fusion reaction. Same as for the Inertial confinement, a capsule of deuterium and tritium is placed at the center of an isolated tank. The plasma is heated and then a pinch of current is send into the plasma (about 20 millions of Amperes). This pinch is called Z-pinch and will instantly contract the plasma and then expands it in response [3]. The contraction phase will lead to the implosion of the capsule which will find itself in temperature and pressure conditions allowing the fusion reaction to happen.

B. Creation of electricity from the nuclear fusion reaction

As mentioned previously, our goal is not experimental but to produce electricity from a nuclear fusion reaction. This raises the question of the recuperation of the heat rejected by the reaction.

In the ITER design, the heat excess is released outside of the plant thanks to cooling shafts. However, the DEMO design will include at its center a series of pipes filled with fluid connected to a closed circuit permitting the creation of electricity thanks to an alternator. For a reactor to be competitive, it also need to be able to run for an unlimited amount of time. This means that the DEMO design will need to develop a technology allowing the exhaust of the Helium nuclei as well as providing at a constant rate the two fuels (deuterium and Lithium) inside the reaction chamber.

For the second and third design, the idea would be to use materials able to contain but also conduct the heat release. The tank inside which the capsule is contained would have to be able to give back the energy it absorbs and transmit it to a balance of plant. Not only this but as the projects are designed, it looks very hard to have a continuous flux of heat getting out of the system as we would have to recharge the combustion chamber in capsules of fuel for each laser bombarding in the second design and each current discharge in the third design. However, we could imagine two reactions chambers working simultaneously one releasing energy when the other is getting refueled.



source : www.slideshare.net/Taimoor_Gondal/nuclear-power-plant-fundamentals

Figure 4 A PWR, a type of balance of plant

For its capacity to create and sustain a chain reaction, the ITER-DEMO project looks more interesting regarding our criteria. [4]

C. Cost of the fusion power and estimated first utilization

All the previous reviewed designs are still experimental but the market penetration of fusion will require the process to be competitive. Nowadays, a project like ITER costs billions of dollars [5] but in the near future, the expected technological improvement could help to drastically reduce the cost and a more detailed knowledge of fusion reactors will allow researchers to find the best trade off between cost and design robustness.

On an economic basis for an energy production, fusion power has a very low variable cost. Once the chain reaction is initiated, the fuel for the reaction chamber is made of cheap and abundant materials. The majority of the cost lies in the construction of the reactor and with the mastering of the technologies used, we will be able to gradually lower this cost. Once a final working design is in operation, the economy of scale will allow the multiplication of reactors around the world and with it a lowering in the price per reactor. The amount of input of capitals needed at the beginning of the project will significantly higher than a regular fossil fueled power plant. Thus to be profitable and make the difference, fusion reactors will have to be built in resistant materials allowing a long period of exploitation which will counterbalance the initial cost. Furthermore, with the growing awareness in our society about climate change and responsible consummation, we can hope that the fusion energy will be massively adopted around the world. To improve the productivity of the power plants, we will have to develop a more efficient power conversion cycle with a reduction to a minimum of the heat loss in the process. Achievement of high efficiency of the power conversion systems depends on availability of reliable high temperature (> 700℃) structural materials, which are still at a very early stage of development. However, with the actual knowledge and advancements, we can estimate that the project DEMO (to be finished by the year 2040) will be able to produce fusion energy based electricity by the year 2050.

IV. CONCLUSIONS

Of all the projects and designs presented, the most accomplished has to be the ITER-DEMO project, an alliance of the US, China, Russia, India and the EU. The design we just reviewed reveals the vastness of the fusion energy exploitation subject. From its calculation, humanity may have found the ways to use the stars energy on earth. Fusion energy could be a major step in the quest of humanity for low cost and abundant energy. The project ITER could actually revolutionize our societies as man won't ever have to worry again about its energy supply again. We will be able to produce energy without limits regardless of fuel rarity and without bad effects on the environment.

The Tokamak design is the most advanced and encouraging design due to the possibility of changing the scale of the reactor but also to keep it running for a theoretical unlimited period of time.

RECOMMENDATION

The magnetic confinement is considered to be the most realizable project in the next years. A first version of the ITER reactor is actually in construction in the south of France and should be ready for tests by 2020. This reactor results from the collaboration of many researchers from all around the world and the interest of the scientific community for this project has brought the public's attention for fusion energy and its possibilities. The promise of a clean, unlimited source of energy that some scientists made in the middle of the nineteenth is actually becoming real in front of our eyes.

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