Energy from Fusion: Containing Plasma to 100 Million Degrees Celsius in the Tokamak

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Abstract: The damage caused to the environment because of the greenhouse gases emissions is mainly due to the use of fossil fuels. These are used for generating energy and they are not renewable resources. The current renewable resources for generating energy, such as wind and solar power, are not capable of being the principal source of energy for the countries. Also, nuclear fission, which is proposed as alternative form of renewable energy, present well known disadvantages like safety and radioactive waste. Fusion energy can fix these problems although it has been complex to develop it to become a massive source of energy. Currently, because of the advancement in physics, science and engineering, it has been possible to develop a method that allows to overcome the greatest difficulty of fusion: containing the fuel to millions of degrees. A recent development, the Tokamak, can carry out and generate energy from fusion given its design and magnetic confinement capacity. With the necessary investment and development of this energy, the growing energy consumption around the world could be satisfied in a clean and safe way.

***Index Terms*— energy, fossil fuels, fusion, magnetic confinement, tokamak**

I. INTRODUCTION[1]

FOSSIL FUELS have been the main energy source for the world in the past few centuries. However, their massive use for energy production has started seriously degrading the environment. Greenhouse gases are causing a significant warming of the planet with consequences such as the melting of glaciers, droughts and disappearance of flora and fauna.

Another energy resource that has been used is nuclear fission. Although it can complement the use of fossil fuels or become the main source of energy for a country, it generates problems related to safety and radioactive waste. In recent years, the renewable energies derived from the wind and the sun have been developed but these methods are not efficient enough to use them as a principal resource [1].

Because of the previously mentioned, one of the National Academy of Engineering (NAE) Grand Challenges For Engineering is to provide energy from fusion. This type of generation of energy is safe, the fuel is abundant, and it does not produce negative effects on the environment.

In order to overcome this challenge, two designs have been developed with the same objective: to overcome a major problem for the generation of energy from fusion. This issue is containing plasma (the fuel of the reactor) to 100 million degrees Celsius [2].

The purpose of this paper is to delve into how engineers have worked so that fusion can become an energy source that can be replicated and made easily accessible. To achieve this aim, firstly, energy use and its increase in the world is analyzed. Secondly, the obstacles and the two designs for fusion generation are presented: the Stellarator and the Tokamak. Finally, this paper focuses on one of these projects, the Tokamak providing a detailed description of its parts, operation and characteristics.

II. ENERGY IN THE WORLD: TYPES OF ENERGY RESOURCES IN RELATION TO THEIR PAST, PRESENT AND FUTURE

Studies have been conducted in order to know the evolution of energy consumption and its current situation with different objectives. One of the most reader-friendly or easy to understand and explain is the one from International Institute for Applied Systems Analysis (IIASA). These studies have been made with the help of the World Energy Council (WEC) and the Intergovernmental Panel on Climate Change (IPCC). In particular, the objective of IIASA studies

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The present manuscript is part of the research activities in the Inglés II lesson at Universidad Tecnológica Nacional, Facultad Regional Paraná. Students are asked to research into a topic so as to shed light on a topic of their interest within the National Academy of Engineering's Grand Challenges or the United Nations' Sustainable Development Goals frameworks. If sources have not been well paraphrased or credited, it might be due to students' developing intercultural communicative competence rather than a conscious intention to plagiarize a text. Should the reader have any questions regarding this work, please contact Graciela Yugdar Tófalo, Senior Lecturer, at gyugdar@frp.utn.edu.ar was to estimate the value for the maximum supply of energy with the consideration of the current technologies and possible new ones that may appear in the next years. Also, the study considers a possible rapid depletion of fossil fuels and the possible maximum contribution and amount of energy possible according to the technology of the moment from each fuel type.

Due to the fact that the study conducted by IIASA goes from 1850 to 2100 different factors are assumed. Because of that, the result of the predictions can be changed for a particular situation. The predictions are for the period of 2012 onwards. Variants regarding population, economic and industrial growth, new technology developments and the availability of primary energy resources are examples of these factors. According to this, in order to understand, three cases are defined [3, Fig. 1]. Case "A" is for a very important and significant advance of technologies with a fast growth of economy that leads to more energy demand. Case "B" is a more realistic scenario, where new technologies are not too advanced and efficient in comparison to the previous case. Case "C" takes into account ecological considerations with progress in the areas related to alternative (non-fossil) energy resources and also relies on international environmental protection.

In [3, Fig. 1], the graph shows the comparison between the consumption of energy for the cases A, B and C. On the vertical axis here is the consumption and in the horizontal axis is the time in years. Case B, the blue curve, because of the considerations for this case (presented in the previous paragraph) it is an intermediate case between A and C. In the graphic this curve, which shows a proportional straight line between the consumption and the years, is considered the most realistic scenario. Because of that, case B is used in the next figures for the study.

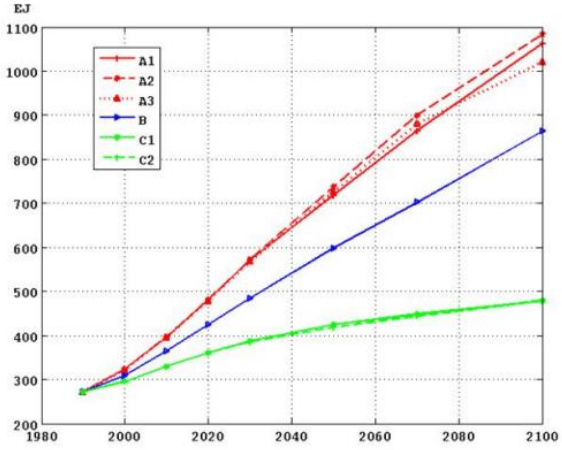

Fig. 1. World Final Energy Consumption until the year 2100 in the IIASA–WEC Study "Global Energy Perspectives" [3].

[3, Fig, 2] shows another prediction from the IIASA–WEC analysis. There is specific growth for different regions of the world. Regions like North America and Western Europe do not present a drastic and considerable change in their primary energy consumption. This is because they are currently the most advanced regions in relation to the energy technologies. On the other hand, for example South and Central Asia will probably have a major energy necessity because of the fact that this region is in an exponential economic improvement.

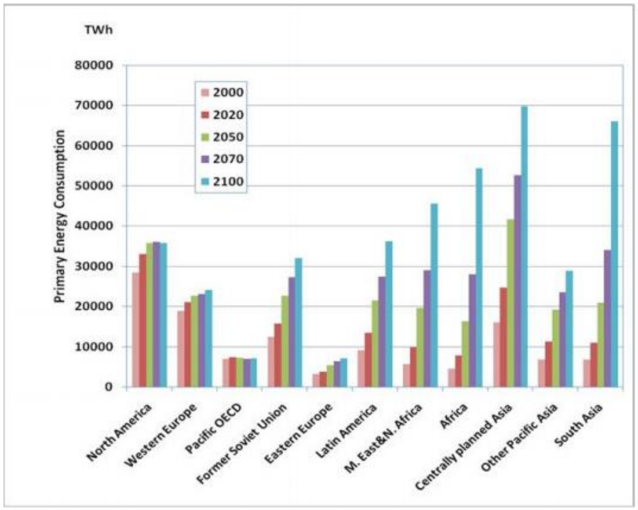

Fig. 2. Region-wise primary energy consumption in IIASA–WEC scenario B [3].

The next graphic, [3, Fig. 3] presents the current situation and the predictions for the use of the different energy resources from 1850 to 2100 for case "B" in the IIASA–WEC analysis. In the future, the participation of the renewable energies will increase with a gradual decrease of the use of the fossil fuels. Although the use of coal still remains constant from 1975 to 2100, this is not the best situation because it can dangerously aggravate the climate change issue.

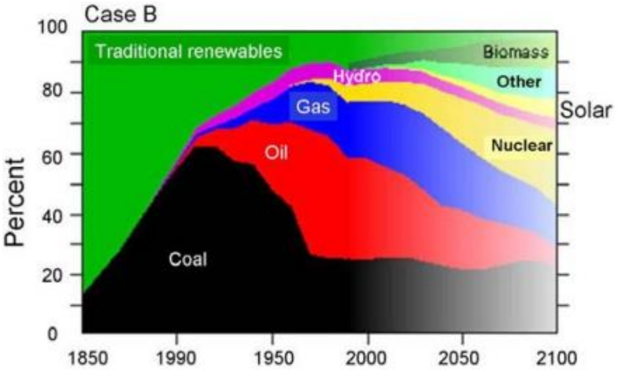

Fig. 3. Evolution of primary energy shares, historical development from 1850 to 1990 and projections till 2100, for Case B [3].

Also, the graph allows to see that the projection for the main replacement of fossil fuels will be nuclear energy, which is divided into nuclear fusion and fission. Neither of them generates pollution. [4, Fig. 4] presents the values for the emission of CO2 to the atmosphere for the different kinds of energy resources. Fusion and fission have 45 times less production of CO2 than a coal reactor of a similar capacity and this can really help to take care of the environment [1].

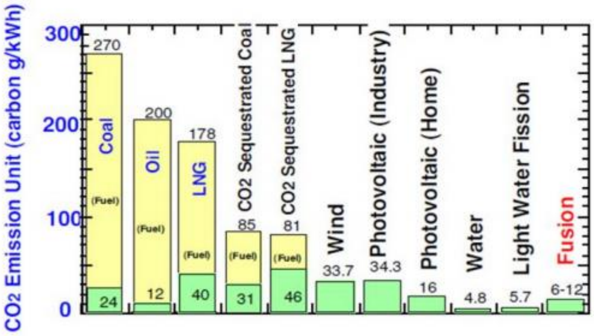

Fig. 4. CO2 emission level of power reactors based on various fuel resources in their entire life cycle, showing fusion reactors as the third lowest CO2 emitter after hydro and fission reactors [4].

In the next years, due to the exhaustion of the fossil fuel resources (estimated 231 years for coal, 63 for natural gas and 44 for petroleum [1]), the renewable energies will satisfy the world's energy consumption. The most important type will be nuclear energy and, as figure 3 shows, this will probably replace oil and gas through the years. For this reason, it is crucial to develop, and invest in this type of energy, especially in fusion.

III. FUSION AND ITS OBSTACLE

As it was stated above, there are two forms of nuclear energy: fission and fusion. Currently, the one that has been used for generating energy is fission. This process consists in bombarding with neutrons a nucleus of a heavy atom that splits into two or more nuclei of lighter atoms. Then, the reaction emits neutrons, gamma rays and large amounts of energy. Although it is widely used, this process has two major issues. Firstly, the reaction can become unstable, compromising the security of the workers, plant and nearby areas. An example of this situation is the disaster that happened in Chernobyl. Secondly, lighter atoms produced by separation of the heavy atom are radioactive. For example, isotopes such as uranium, plutonium and cesium, which have no applications become radioactive waste [1].

On the other hand, nuclear fusion is the process by which two light atoms combine to form a heavier atom [5]. The difference of mass between light atoms and the heavy atom results in the release of energy (see explanation below). For this to happen, for example, two hydrogen atoms have to be thrown together with enough energy to overcome the repulsive forces that negative electrical charges generate to the atoms. In this way, the hydrogen atoms can get so close to each other that their nuclei fuse [5].

According to [1], fusion presents some advantages to consider exploiting:

1) Fuel is plentiful.
2) Fusion fuel is readily accessible from everywhere.
3) There are limited radioactive waste problems. None of the fusion reaction products are radioactive in the first place.
4) The fusion reaction is inherently safe. There is no danger of runaway reactions, criticality or a meltdown.
5) There are no dangers of proliferation or of a terrorist group or fringe group running away with key materials which may be put together to form a crude device.

The energy radiated by the sun and stars is the result of natural nuclear fusion. This discovery arises after Albert Einstein deduced that mass can be converted into energy, which can be observed from his equation $E = mc^2$. Years later Francis Aston, with his precise measurements of atomic masses, showed that the mass of one helium atom is slightly minor than the total mass of four hydrogen atoms. With these two results, Arthur Eddington and others, proposed that energy in the Sun and stars could come from the combination that Aston studied (four hydrogen atoms to a helium atom). According to classical physics, the Sun was not hot enough for fusion to take place. After quantum mechanics was developed, fusion could be completely understood [5].

Replicating the Sun's natural fusion on Earth presents a main obstacle. Fusion needs to be generated from plasma made up of deuterium and tritium (hydrogen isotopes) at a temperature of 100 million C°. Evidently, there is no material with mechanical properties capable of withstanding such a temperature. For this reason, engineers have been challenged to design a reactor capable of carrying out nuclear fusion to use the energy released from this reaction and its advantages over fission.

IV. THE TWO FUSION PROPOSALS

There are two possible options to solve the controlled thermonuclear fusion problem. The first one is isolating a relatively rarefied quasi-stationary, almost static, plasma using an external magnetic field. This can be done in fusion reactors with magnetic confinement. The second is obtaining a dense hydrogen fuel capsule compressed from all sides in a pulsed mode, then heating the fuel to "melting" temperatures and burning it. The reactors that can do this process are the inertial confinement fusion reactors [6]. This article discusses the first option.

Following the previous principle, magnetic confinement, the theorical foundations for the first fusion reactor version was laid at the beginning of 1950. Igor Tamm and Andrei Sakharov proposed a toroidal plasma column in a strong longitudinal magnetic field, which became a tokamak prototype. The word "tokamak" is a Russian acronym for "toroidal chamber with magnetic coils". One year later, Lyman Spitzer, who was an American astrophysics, developed the idea of a stellarator, which is another type of a toroidal magnetic confinement device [6].

A stellarator is very closely related to the tokamak, but the difference is how the confining magnetic field is achieved. The tokamak uses a combination of plasma current and toroidal fields coils and the stellarator employs helical coils. The basic physical concept of the stellarator magnet system is very complex. [6, Fig. 5] shows a basic model that compares the form of the fields coils in both designs, the ones for the stellarator are more complicated than the ones for the tokamak. Another disadvantage is that at equal plasma volumes, a stellarator is larger than a tokamak [6]. Although these advantages are not too significant, the design of the tokamak is more practical. The characteristics of this will be developed in the next section.

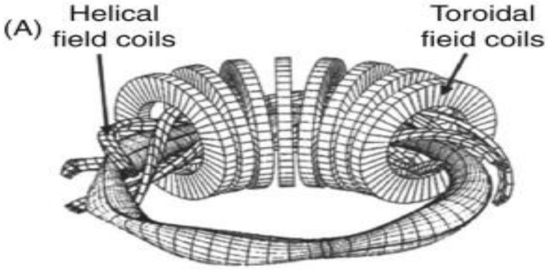

Fig. 5. Comparation of the field coils from a stellarator and a tokamak [6].

V. TOKAMAK

The heart of a tokamak is its vacuum chamber, which is doughnut shaped. Inside, gaseous hydrogen fuel becomes a plasma (a hot and electrically charged gas) because of influence of extreme heat and pressure. The environment in which light elements can fuse and yield energy is provided by the plasma. In order to confine the hot plasma away from the vessel walls physicists use the next property: the charged particles of the plasma can be shaped and controlled by the massive magnetic coils placed around the vessel.

The process starts with the evacuation of air and impurities from the vacuum chamber. Then, the magnet systems that will help to confine and control the plasma are charged up and the gaseous fuel is introduced. The gas breaks down electrically, becomes ionized and forms a plasma because of a powerful electrical current that run through the vessel.

As the plasma particles become energized and collide, they also begin to heat up. To help to bring the plasma to fusion temperatures an auxiliary heating method is used. Now, the particles are very energized so they can overcome their natural electromagnetic repulsion and they collide to fuse, releasing huge amounts of energy [7].

The machine to carry out this process has some important parts. A brief explanation of them will be given below. Specifically, these parts are from the International Thermonuclear Experimental Reactor (ITER). This reactor will be the world's largest tokamak and it is projected to be finished by 2025 [7].

A. Magnets

In this component, there are ten thousand tons of superconducting magnets. They will produce the magnetic fields to initiate, confine, shape and control the ITER plasma. [7, Fig. 6] shows this component in blue.

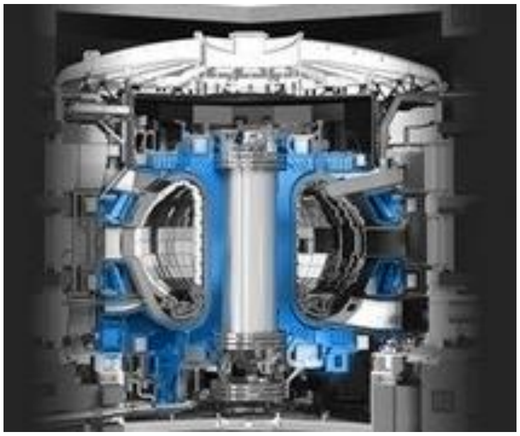

Fig. 6. Magnets from ITER´s tokamak [7].

B. Vacuum vessel

The stainless-steel vacuum vessel houses the fusion reactions. Also, it acts as a first safety containment barrier. [7, Fig. 7] shows this part in orange.

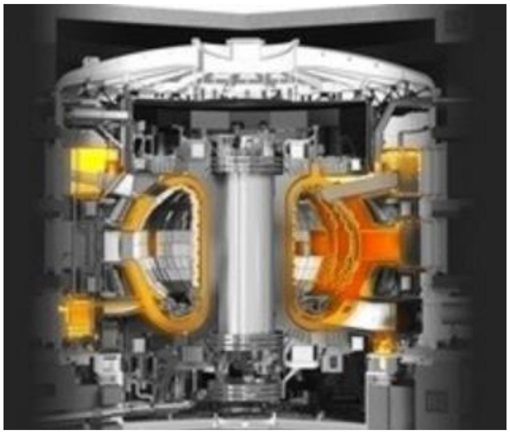

Fig. 7. Vacuum vessel from ITER´s tokamak [7].

C. Blanket

The blanket shields the steel vacuum vessel and external machine components from high-energy neutrons produced during the fusion reaction. This component is shown in [7, Fig. 8] in red.

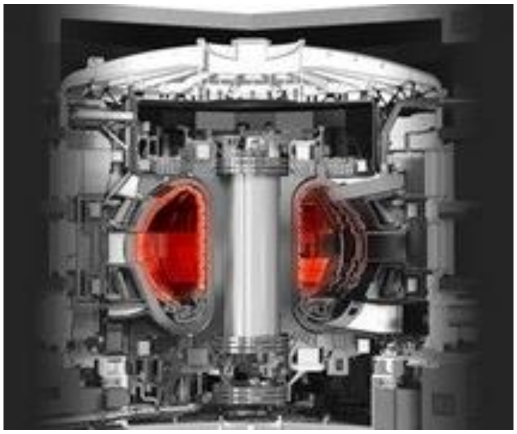

Fig. 8. Blanket from ITER´s tokamak [7].

D. Divertor

Positioned at the bottom of the vacuum vessel, the divertor controls the exhaust of waste gas and impurities from the reactor and withstands the highest surface heat loads of the ITER machine. This part is shown in [7, Fig. 9] in blue.

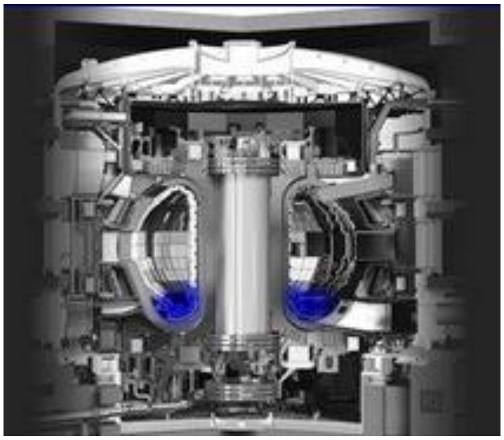

Fig. 8. Divertor from ITER´s tokamak [7].

E. Cryostat

The stainless-steel cryostat surrounds the vacuum vessel and superconducting magnets and ensures an ultra-cool, vacuum environment. [7, Fig. 10] shows the cryostat in green.

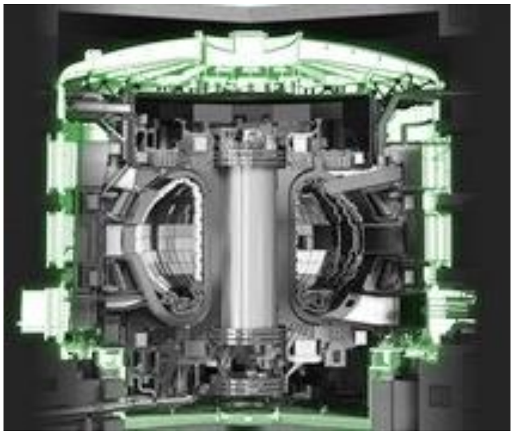

Fig. 8. Cryostat from ITER´s tokamak [7].

With this process and design fusion can be possible. The tokamak from ITER can produce 500 MW of energy in a secure and efficient way [7].

VI. CONCLUSION

As seen previously, fusion has significant advantages such as plentiful and accessible fuel. As well as this, it has no radioactive waste and low CO2 emission. With the design of the tokamak, it will be possible to generate energy massively and perhaps will become a principal energy resource for the countries in the future. It is important because it can replace the fossil fuels that have degraded and damaged the environment in the last's decades. However, carbon fuel will go on being used but it is crucial to keep developing and investing in fusion technology with the objective of reducing the use of the carbon fuel. Continuing to improve energy generation methods through fusion is a task for current and new generations of engineers.

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