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A little about nuclear fusion

Mesquita[a*,] A. Z.

[a]Reactor Technology Department - Nuclear Technology Development Centre/Brazilian Nuclear Energy Commission (CDTN/Cnen)

*Correspondence: amir@cdtn.br

Abstract: On December 20, 1951, Experimental Breeder Reactor No. 1 (EBR-I), located at Argonne National Laboratory, produced enough electricity to power four light bulbs. From these modest beginnings, the civilian application of nuclear energy became a reality. The first nuclear power plant to generate energy connected to the electrical grid took place on June 27, 1954, in Obninsk (Soviet Union). There are currently around 440 nuclear reactors in operation, distributed across 50 countries. They all produce energy through the process of uranium-235 nuclear fission. However, as is well known, the conversion of mass into energy also occurs with light nuclei. When hydrogen and deuterium fuse to form a heavier nucleus, such as tritium and helium, they release energy. Stars are the largest fusion reactor power plants. A star is initially just a cloud of hydrogen. The gravitational attraction brings hydrogen atoms together, increasing pressure, density, and temperature. Kinetic energy causes collisions to the point where electrons are separated. The mass of nuclei and electrons forms plasma, which is the fourth state of matter. Hot plasma from nuclei meets the conditions for the initiation of fusion reactions. Two techniques have been developed to enable energy production in fusion reactors. The oldest (started in the mid-1950s) is magnetic confinement, in which plasmas at thermonuclear temperatures are confined by appropriate magnetic fields. The latest technique for performing fusion (begun in the late 1960s) is inertial confinement, in which tiny solid targets are compressed to very high densities using laser beams. This article briefly recalls the fundamental concepts of the energy released by nuclear fusion.

Keywords: Nuclear fusion, plasma, nuclear force, hydrogen, ITER®, laser, nucleus.

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Um pouco sobre a fusão nuclear

Resumo: Em 20 de dezembro de 1951, o *Experimental Breeder Reactor No.* 1 (EBR-I), localizado no Argonne National Laboratory, produziu eletricidade suficiente para alimentar quatro lâmpadas. A partir deste início modesto, a aplicação civil da energia nuclear tornou-se uma realidade. A primeira usina nuclear a gerar energia conectada à rede elétrica ocorreu em 27 de junho de 1954, em Obninsk (União Soviética). Existem atualmente cerca de 440 reatores nucleares em operação, distribuídos por 50 países. Todos eles produzem energia através do processo de fissão nuclear do urânio-235. Porém, como é bem sabido, a conversão de massa em energia também ocorre com núcleos leves. Quando o hidrogênio e o deutério se fundem para formar um núcleo mais pesado, como o trítio e o hélio, eles liberam energia. As estrelas são as maiores usinas de reatores de fusão. Uma estrela é inicialmente apenas uma nuvem de hidrogênio. A atração gravitacional une os átomos de hidrogênio, aumentando a pressão, a densidade e a temperatura. A energia cinética causa colisões até o ponto em que os elétrons são separados. A massa de núcleos e elétrons forma o plasma, que é o quarto estado da matéria. O plasma quente dos núcleos reúne as condições para o início das reações de fusão. Duas técnicas foram desenvolvidas para permitir a produção de energia em reatores de fusão. O mais antigo (iniciado em meados da década de 1950) é o confinamento magnético, no qual plasmas em temperaturas termonucleares são confinados por campos magnéticos apropriados. A técnica mais recente para realizar fusão (iniciada no final da década de 1960) é o confinamento inercial, no qual minúsculos alvos sólidos são comprimidos a densidades muito altas usando feixes de laser. Este artigo relembra brevemente os conceitos fundamentais da energia liberada pela fusão nuclear.

Palavras-chave: Fusão nuclear, plasma, força nuclear, hidrogênio, ITER®, laser, núcleo.

1. INTRODUCTION

Fusion reactions of the nuclei of light atoms release an amount of energy more than a million times greater than a typical chemical reaction. This enormous amount of energy occurs because the mass of the nucleus produced is less than the sum of the masses of the initial nuclei. The lost mass is converted into energy. Although fusion is an energetically favorable (exothermic) process for light nuclei, it does not occur naturally here on Earth, due to the natural difficulties of bringing reactants together (due to electrostatic repulsion between the two nuclei) so that nuclear forces can act. Fusion reactions have been happening for billions of years in the universe. In fact, fusion reactions are responsible for producing energy in most stars, including the Sun. Scientists on Earth have only been able to produce nuclear fusion reactions in the last 60 years. Fusion between heavier nuclei is routinely produced in small quantities in particle accelerators. Nuclear fusion is the basis of our lives, since the solar energy produced by this process is essential for maintaining life on Earth [1].

When a star is created, it consists of hydrogen and helium generated in the Big Bang, the process that gave rise to the universe. Due to the enormous gravitational field, hydrogen atoms in the star collide and fuse to form helium nuclei. Later, helium, colliding with hydrogen and other helium nuclei, gives rise to heavier elements. These reactions continue until iron is formed. From Fe onwards, fusion no longer occurs in the star. The process becomes energetically unfavorable. When a star has converted an appreciable fraction of its hydrogen and helium into heavier elements, it moves into the final stage of its life. Some stars begin to contract, into a sphere made up largely of iron. However, if the star's mass is large enough, a tremendous, violent, and bright explosion can occur. The star suddenly expands and produces, in a short time, more energy than the sun will produce in its entire lifetime. When this occurs, the star becomes a supernova. When the star is in the supernova phase, many important nuclear reactions take place. In the explosion, the nuclei are accelerated to speeds much greater than those they normally have in the star. In the new condition, the high-speed nuclei collide and can now fuse, producing elements with a mass greater than that of iron. The extra energy from the explosion is needed to overcome the enormous repulsive force between the nuclei due to the nuclear electrical charge. Elements such as lead, gold, and silver found on Earth were once leftovers from a supernova explosion. The iron that we find on much of the Earth's surface, as well as in its core, comes from both the remains of supernovae and dead stars [1].

When a gas is heated to several thousand degrees, the particles separate into parts (molecules dividing or atoms losing electrons, that is, becoming ionized), giving rise to the state of matter called plasma. The study of plasma is of interest for carrying out controlled thermonuclear fusion. It would be a very abundant source of energy and much cleaner than that of nuclear fission, used in common nuclear power plants. It is said to be "controlled" in contrast to the energy generated in the explosions of hydrogen bombs (H bombs). The technical and theoretical problems involved in carrying out controlled fusion are immense. Research on the subject has been going on for 60 years and it may be another 60 years before the first controlled fusion plant begins to produce electricity commercially. Large fusion experiments, based on systems called tokamaks, are being built. The most promising is ITER®, in the south of France, which involves the collaboration of several countries (European Union, Japan, USA, Russia, China, India and South Korea) [2].

As a plasma suitable for fusion would be very hot – tens of millions of degrees Celsius, it cannot be contained normally: contact with the material walls must be avoided (this, in addition to damaging them, would also cool the plasma). To do this, you can take advantage of the fact that it is basically made up of electrically charged particles. Because, due to the high temperature, the atoms would lose their electrons, becoming electrically positive. Thus, magnetic fields and electric currents induced in the plasma are used to conveniently divert the trajectories of the particles (which normally move quickly and randomly back and forth), to always keep them within a region of space. This is called “magnetic confinement” [2].

Working with the theory of stimulated radiation emission formulated by Einstein (1917) [3], the American physicist and engineer Theodore Harold Maiman, was the first to build a Laser (Light Amplification by Stimulated Emission of Radiation) on May 16, 1960. Maiman's (1960) experiment was based on the work of other pioneers such as Gordon Gould, Charles Townes, and Arthur Schawlow. Maiman (1960) [4], shined a high-power light on a ruby partially covered with silver and the result was the world's first laser.

Currently, after more than sixty years there are thousands of applications of lasers, both for basic science and in use directly for the benefit of humanity. In December 2022, the experimental confirmation of one of the applications, which has been attempted for more than fifty years, was announced. That is, the production with gain of fusion energy through the inertial confinement scheme. In the experiment carried out by scientists from the National Ignition Facility – NIF, at Lawrence Livermore National Laboratory – LLNL. The so-called ignition condition was reached, in which the energy released by the fusion reactions between deuterium and tritium, supplants the energy provided by the laser beam. used to initiate reactions [5].

2. NUCLEON BINDING ENERGY

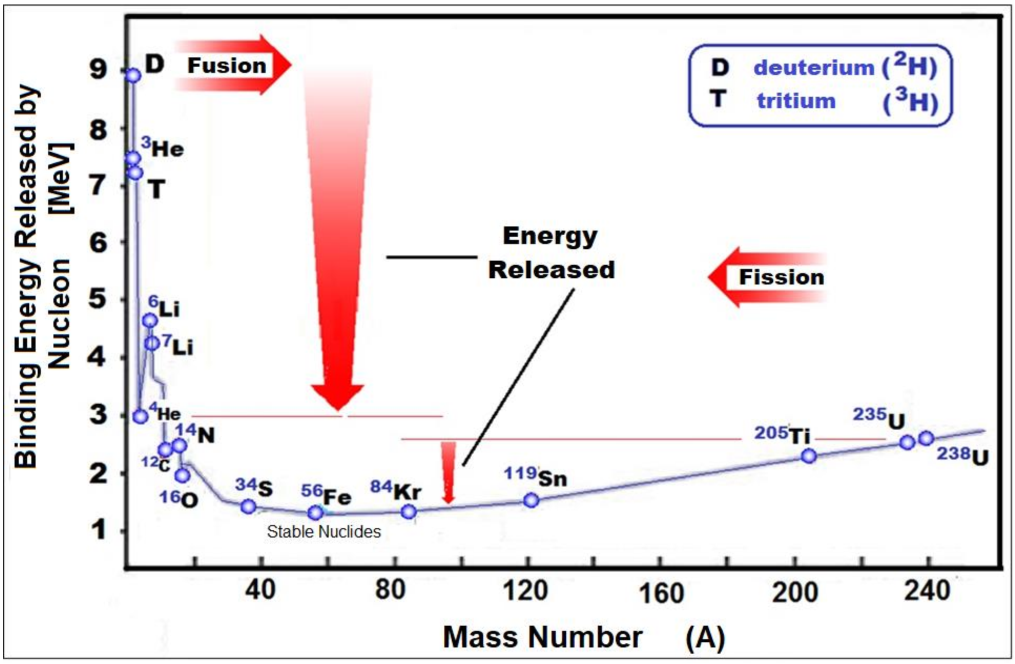
The use of nuclear energy is possible due to the so-called mass “deficits” of the nucleus. That is: the mass of the compound atoms is not equal to the sum of the masses of the components involved. For example, in the formation of the helium nucleus, energy is released by the fusion of hydrogen atoms. On the other hand, the fission of uranium forming two lighter elements energy is released. In both cases, a small portion of mass is transformed into energy, given by Einstein's famous equation:

$$E = mc^2 \quad (1)$$

Where m is the mass loss and c is the speed of light in a vacuum (3 x 10^8 m/s).

In Figure 1, a graph is presented showing the energy released per nucleon, as a function of the mass number (A). This graph is normally shown in an inversely, that is, it shows the binding energy per nucleon, which is the energy required to separate a neutron or a proton from the nucleus. For light nucleons, the binding energies per nucleon show an increase until reaching a maximum value of 8.7 MeV. For nuclides with approximately 50 or 60 nucleons (iron and nickel) then gradually decrease until reaching 7.5. MeV for uranium-238. The decrease is more pronounced from A > 150 because of the Coulomb repulsion between the protons. This repulsion, which is small compared to the nuclear force, becomes relatively more important for nucleons with high Z values. This is why there is a limit to the number of stable elements that can be formed.

Figure 1: Binding energy released by nucleon



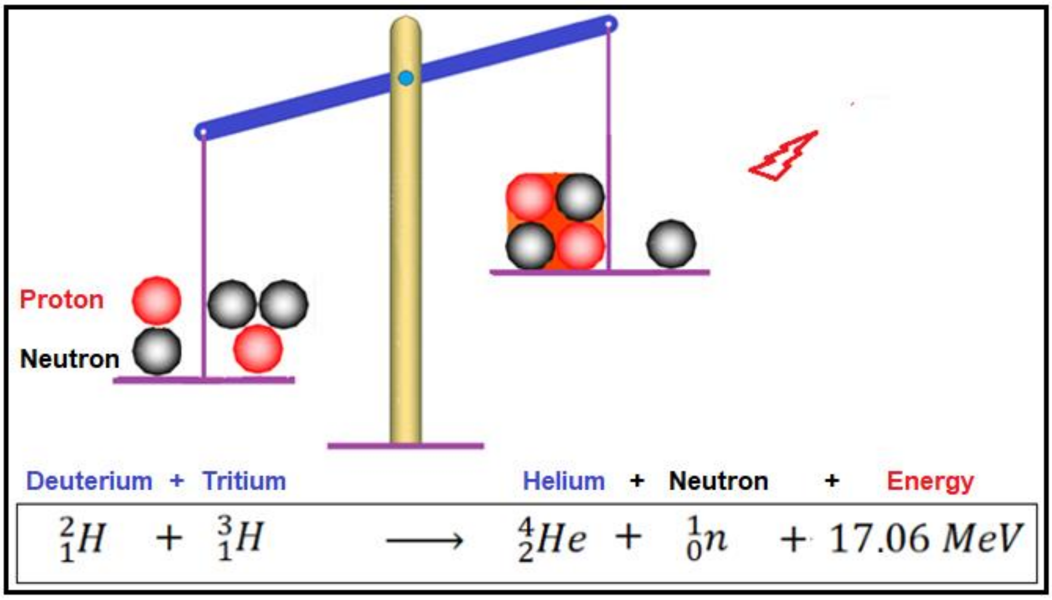
Source: Mesquita (2023) [6]

Nuclei that have higher binding energy per nucleon are more stable. In the curve shown in Figure 1, there are two ways in which energy can be released by atomic nuclei, namely, fusion of light nuclei or fission of heavy nuclei. In both processes, the new nuclides formed have smaller masses than the original nuclide. This difference in mass is transformed into energy (Eq. 1).

The fusion of hydrogen forming helium is the source of energy for stars like our Sun. The fission of uranium-235 is used in nuclear reactors to produce heat and electricity. Most forms of energy used by man originate from the Sun, either as fossil fuels or even with the direct use of solar energy. The big exception is nuclear energy[1] .

An example of fusion is the formation of helium, which is lighter than the set of its components: a proton, a neutron, and H-3 (tritium or T), as illustrated in Fig. 2. Equivalent process occurs in the splitting of heavy elements (fission), when a smaller amount of mass is transformed into energy.

Figure 2: Mass transformed into energy in the formation of helium



Source: Mesquita (2023) [6]

[1] Geothermal energy also does not come from the sun but from the heat of the Earth's core, including the decay of radioactive elements present there, mainly: U-238, Th-232 and K-40. Other types of energy, used in reduced quantities, also do not originate from the Sun, such as tidal energy and thermoelectric generators.

An example of a fusion reaction is the combination of two hydrogen nuclei with two neutrons to form helium, as shown below:

$$2\,{}_{1}^{1}H + 2\,{}_{0}^{1}n \rightarrow {}_{2}^{4}He \tag{2}$$

Using the differences in atomic mass, we have:

$$2(1.007825) + 2(1.008665) - 4.002603 = 0.030377 \text{ amu} \tag{3}$$

This mass value (**0.030377 amu**) corresponds to **28.3 MeV** of energy.

The energy released in the fusion of deuterium with two neutrons, per unit of atomic mass (28.3 MeV/4), is around 7 MeV. It is around nine times greater than the energy of fission of uranium-235 per unit of atomic mass (200 MeV/235), which is equal to 0.8 MeV.

Several reactions are possible combining hydrogen nuclei (${}_{1}^{1}H$) and their isotopes. Deuterium (${}_{1}^{2}$H or D) and tritium (${}_{1}^{3}$H or T), or using other light elements such as lithium (Li), boron (B) and helium (He), always releasing energy. A very promising fusion reaction uses deuterium ${}_{1}^{2}$H, and the isotope helium-3, as follows:

$${}_{1}^{2}H + {}_{2}^{3}He \rightarrow {}_{1}^{1}H + {}_{2}^{4}He + 18.3\ MeV \tag{4}$$

Different approaches and experiments to achieve fusion with energy gains have been in evidence in several countries in recent years. The two best-known processes in research into the fusion of the nuclei of light chemical elements are presented below.

3. MAGNETIC CONFINEMENT OF PLASMA

The conditions to trigger fusion chain reactions are very high temperatures and pressure. These conditions have been achieved, since 1949, with the hydrogen bomb, or thermonuclear bomb (uncontrolled fusion), which is initiated with the detonation of a fission device. Controlling the fusion reaction has been attempted for several years, but, to date, it has not been possible to maintain the chain reactions in such a way that there is a positive gain in energy. In other words, more energy is spent to create and maintain the plasma confined than the energy that can be used. Plasma is the fourth state of matter, the other three being solid, liquid, and gas. It is in the plasma that fusion reactions take place.

The most common way to confine the plasma has been through a magnetic field provided by powerful electromagnets, which produce a toroidal magnetic field. Plasma is formed by the isotopes of hydrogen, deuterium, and tritium. The magnetic field limits the space where fusion occurs, so as not to touch the walls of the reactor vessel, otherwise the walls would be damaged, in addition to cooling the plasma. Plasma particles normally move in all directions due to their very high kinetic energy. As they are electrically charged, the magnetic field directs them around the center of the toroid. Positive particles rotate in one direction and negative particles (electrons) in the opposite direction. They do not leave the magnetic field lines of force and do not reach the walls. Thus, collisions eventually occur, generating fusion energy. Neutrons formed in fusion reactions carry energy to walls and heat removal systems. One of the difficulties with fusion reactors is that the nuclear reaction product needs to be removed from the system, as it is an impurity.

Almost all experimental research at present is based on magnetic confinement using the controlled fusion reaction of deuterium and tritium (D-T). Because, it demands the highest cross section, at the lowest plasma temperature to overcome electrostatic repulsion, according to the reaction:

$$ {}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.06\,MeV \qquad (5) $$

Deuterium is stable and has an average abundance of 0.015% of the hydrogen content of water on our planet (${}^{1}_{1}H$ has an abundance of 99.98%). Tritium is radioactive with a half-life of 12.3 years, decaying into He-3, and emitting beta (β) particles. Its abundance is scarce and is obtained by neutron activation reaction of the isotope lithium-6 and lithium-7[2], with neutrons in a nuclear research reactor or using the neutrons generated in Eq. 5, according to the reactions (Eq. 6 and Eq. 7):

$$ {}^{1}_{0}n \;+\; {}^{6}_{3}Li \;\longrightarrow\; {}^{4}_{2}He \;+\; {}^{3}_{1}\boldsymbol{H} \;+\; 4.78\,MeV \tag{6}$$

$$ {}^{1}_{0}n \;+\; {}^{7}_{3}Li \;\longrightarrow\; {}^{4}_{2}He \;+\; {}^{3}_{1}\boldsymbol{H} \;+\; {}^{1}_{0}n \;-\; 2.74\,MeV \tag{7}$$

The first assembly by magnetic confinement went into operation in 1956 at the Kurchatov Institute in Moscow, being known as Tokamak[3] (**TO**roidal'naya **KA**mera s **MA**gnitnymi **K**atushkami) “toroidal chamber with magnetic coils”. It was devised by Soviet physicists. From that time until today it has been perfected, but the same principle has always been maintained. There are dozens of tokamaks distributed across several countries.

A variation of magnetic confinement is the stellarator. The most advanced currently is at the Max Plank Institute in Germany called Wendelstein 7-X (W7-X). Tokamaks are subject to magnetic disturbances that can destabilize the entire reactor. Differences in the way magnetic fields are created make stellarator immune to these problems. However, stellarators are much more complex to build. While tokamaks are better at keeping plasmas hot, stellarators are better at keeping them stable. Despite the current prevalence of the tokamak, it is still possible that stellarators could one day become the preferred option for a future fusion power plant. About 60 tokamaks and 10 stellarators are currently operating [7].

3.1. The ITER® Organization – The Way

Currently, the most advanced Tokamak under construction is ITER®, “The Way” in Latin (previously an acronym for: International Thermonuclear Experimental Reactor), located in Cadarache, in the south of France. Its construction began in 2013 and is expected

[2] Li-6 and Li-7 are stable and have abundances of 7.5% and 92.5%, respectively. It is a material found in considerable quantities in the earth's crust and seawater.

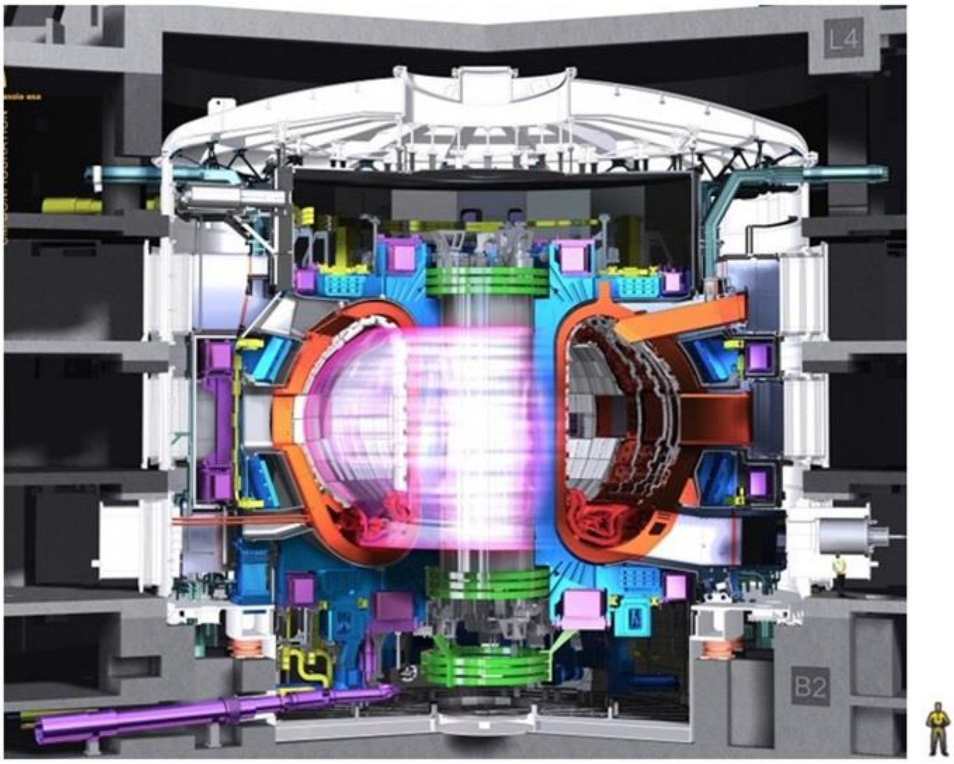
[3] Acronym of the Russian term: тороидальная камера с магнитными катушками

to be completed in 2025, when its commissioning and plasma experiments will begin. Full deuterium-tritium (D-T) fusion experiments will begin in 2035. The project is an international cooperation involving the European Union, China, India, Japan, South Korea, Russia, and the United States, with the support of International Atomic Energy Agency (IAEA). It will be the largest assembly of its kind in the world, twice the size and ten times the volume of the plasma chamber of the largest machine currently in operation.

Its thermal power will be 500 MW, ten times greater than the power to be consumed by the system, which will be 50 MW. Producing a positive gain in energy is the objective of the installation. The conversion of nuclear energy into electricity is not the major objective of the project. The plasma temperature will reach 150 x 106 ^{o}C. The plasma radius will be 6.2 m and its volume 840 m^3. The magnet coils will be made of a niobium and titanium alloy weighing 10 tons. They will be cooled to a temperature of 4 K (-269 ^{o}C) in supercritical helium, becoming superconductors. There will be 18 “D” shaped toroidal field electromagnets, placed around the vessel producing the magnetic field. The main function of the vessel is to confine plasma particles. The ITER® experiments will take place inside this hermetically sealed, vacuum-sealed steel vessel, which houses the D-T fusion reactions and acts as the first safety containment barrier. In its tire-shaped chamber (torus), plasma particles spiral continuously without touching the walls. Figure 3 shows a diagram of the ITER® tokamak. An image of a person is shown to highlight the dimensions of the system.

As can be seen, inside the ITER® tokamak there will be a large temperature difference over a small distance, that is: 150 million ^{o}C in the plasma and almost zero kelvin (K) in the superconductors. The electrical conductors of the coils will be made of an alloy containing niobium. It is noteworthy that Brazil concentrates approximately 92% of production and more than 98% of global niobium reserves, with the largest reserves located in the state of Minas Gerais [8].

Figure 3: Sectional drawing of the ITER® tokamak



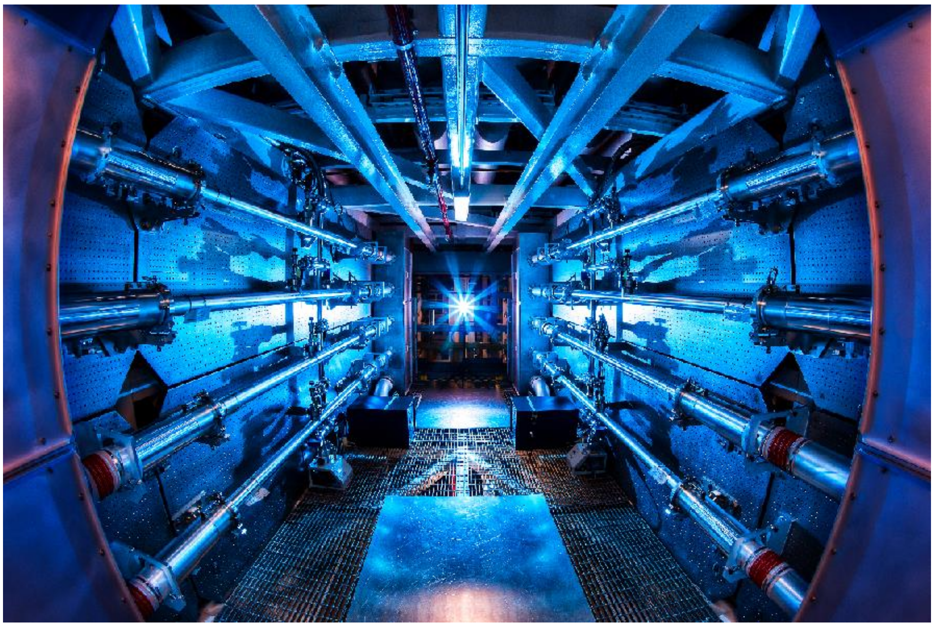
Courtesy: ITER® Organization [9].

4. INERTIAL CONFINEMENT - LASER FUSION

The United States Department of Energy (DOE) and the DOE National Nuclear Security Administration announced on December 13, 2022, that researchers at the National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory (LLNL) in California have achieved more energy than laser beams used to initiate nuclear fusion reactions. Laser fusion experiments have been attempted for decades to achieve high levels of temperature and pressure to fuse nuclei. But no nuclear fusion experiment had been able to produce more energy than the laser energy used in the experiments (laser fusion) (Fig. 4) [10].

A powerful 192-beam laser entered the top and bottom of a small metal cylinder. Inside was a plastic capsule the size of a small pea (about 4.6 mm in diameter) containing 150 micrograms of the two isotopes of hydrogen (fuel). The sudden heating of the cylinder generated an internal X-ray attack that compressed the deuterium and tritium (DT or H-2 and H-3) fuel pellet. In a moment, lasting less than 100 trillionths of a second, it uniformly increased the surface temperature of the capsule to 100 million degrees Celsius (°C), about 10 times what stars reach in fusion. The 2.05 megajoules (MJ) of laser energy inside the cylinder, equivalent to about half a kilogram of TNT, bombarded the DT pellet. This heat caused the capsule to explode and generated a shock wave that compressed the mixture of deuterium and tritium and caused nuclear fusion. Thus, neutrons and alpha particles (He nucleus) were released. The neutrons escape, but the alpha particles deposit their energy into the dense fuel, heating it further. 3.15 MJ of energy was released from the fusion reaction, a factor of 1.54 gain in relation to the energy input [11] [12].

Figure 4: Interior of a National Ignition Facility (NIF) preamplifier support structure.



Courtesy: LLNL - Lawrence Livermore National Laboratory. Credit: Jemison, D. [13]

This passed the threshold that laser fusion scientists call ignition, the dividing line where the energy generated by fusion is equal to the energy of the incoming lasers that initiate the reaction [14]. What has not been fully disclosed is that to produce the laser beam, around 150 times more electrical energy was used than was produced in the process [15].

Although a significantly greater energy gain is needed to produce energy, the experiment represented a huge step forward in fusion research. The laser is so strong that it can heat the capsule to 100 million ^{o}C. Temperature higher than that of the Sun and equivalent to the temperature that would occur if the Earth's atmosphere were compressed 100 billion times. Under these forces, the capsule begins to implode in on itself, forcing the hydrogen atoms to fuse, releasing energy.

Although the experiment produced a net gain in energy compared to the energy of the 2.05 MJ from the incoming laser beams, 300 MJ from the mains was required to energize the laser to generate the brief pulse. The laser used is the most powerful in the world, but it is slow and inefficient, relying on decades-old technology. The device, the size of a sports stadium, was designed to perform basic scientific experiments, not to serve as a prototype for generating electricity. He performs an average of 10 laser pulses per week. A commercial installation using the laser fusion approach would need much faster lasers, capable of firing at the rate of a machine gun, perhaps 10 times per second. The laboratory still consumes much more energy than that produced by fusion reactions. Other types of lasers are more efficient. The researchers calculate that a viable laser fusion power plant would likely require energy gains much greater than the 1.5 observed in this recent fusion experiment. Gains of 30 to 100 would be needed to make energy supply viable in a plant [16].

5. CONCLUSION

Fusion reactions constitute the source of energy for the largest power plants in the universe: the stars. Although a star is initially just a cloud of hydrogen, contraction, caused by its own gravitational pull, increases pressure, density, and temperature. The collisions between atoms increase in number and violence, until they begin to release their electrons, forming plasma. Stars carry out this process spontaneously. The effect of its gravitational field is so enormous that, naturally, it promotes extreme compression of the nuclei of these two isotopes of hydrogen, creating ideal conditions for nuclear fusion to occur.

Two schemes are used to enable energy generation in nuclear fusion reactors. The oldest system began to be researched in the 1950s and is known as magnetic confinement. In this system, plasmas reach very high temperatures, being confined by magnetic fields in a toroid-shaped reactor. These are the well-known tokamaks developed in the former Soviet Union [5].

The most recent technique, which began in the 1960s, is inertial confinement fusion. It uses laser beams that fire for a few billionths of a second to generate x-rays. The x-rays compress and heat a tiny fuel capsule (deuterium and tritium) the size of a peppercorn pea (about 4.6 mm in diameter). Subsequently, the fuel becomes hot and dense enough to form a plasma. The hydrogen nuclei begin to collide, fusing and releasing energy. It was in this type of experiment that in 2022 at the Lawrence Livermore National Laboratory (LLNL) more energy was obtained than the energy of the laser beams used to initiate nuclear fusion reactions [17].

While both techniques aim to create plasma hot enough to fuel fusion, the physics and engineering required to get there differ in several respects.

However, controlled nuclear fusion is still in the research phase and it could take decades before electricity is produced through this way. However, the prospects are attractive due to the abundance of deuterium in nature. The main project that aims to demonstrate the commercial viability of using controlled nuclear fusion through magnetic plasma confinement is ITER®, based on tokamak technology.

A nuclear fusion process that was in the news a lot recently was fusion with energy gain using laser beam. The experiment was carried out by researchers at Lawrence Livermore National Laboratory (LLNL) in California. But it is very likely that the laser beam fusion process will never be used to supply electrical energy. This is a very expensive and inefficient way to cause nuclear fusion. The objective of the experiment carried out was to demonstrate that it is possible to obtain energy gains with fusion using laser beams.

Researchers at other institutes are analyzing variations of the experiment carried out. Other types of lasers at different wavelengths can heat hydrogen more efficiently. Some researchers suggest using "direct drive" for laser fusion, using laser light to directly heat hydrogen[4]. This would put more energy into the hydrogen, but it could also create instabilities that would impede fusion reactions.

Critics of research to develop fusion reactors often belittle efforts in this area with the facetious comment that "fusion reactors are always thirty years in the future." This scientifically retrograde attitude is worth countering with the statement of Dr. Arati Prabhakar, Chief Advisor for Science and Technology to the President of the United States of America, when commenting on the NIF result,

> "We have had a theoretical understanding of fusion for over a century, but the journey from knowing to doing can be long and arduous. Today's milestone shows what we can do with perseverance" [5].

Germany was one of the main countries to develop and use fission nuclear power plants. However, its use for generating electrical energy was abolished after the Fukushima accident. Now, in 2024, Germany's Federal Minister for Research Bettina Stark-Watzinger, has announced a new funding program called "Fusion 2040". This is an ambitious funding program for research into nuclear fusion. The objective is to pave the way for the construction of the country's first nuclear fusion plant by 2040. The program will have two phases: the first for the development of technologies, components and materials needed for a fusion plant by the beginning of 2030. In the second phase, the focus will be on the integration of a central project, explains the minister. Together with the resources already allocated to research institutions, the German government intends to make more than one billion euros available for nuclear fusion research by 2028, involving universities, research institutes and industry [18] [19] [20].

[4] Without transforming the laser beam into an X-ray for attack inside the cylinder.

Nuclear fusion energy stands as a highly promising option to meet future energy demands. However, its realization requires the development of materials capable of withstanding the extreme conditions within forthcoming power plants.

Light nuclear fusion experiments are important and will be the future of nuclear energy without waste. But it will take a few decades to achieve this. Until then, the only clean and sustainable energy available, which humanity has dominated and controlled since the first nuclear reactor in 1942, is uranium fission, which will continue to dominate for several decades.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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