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ENERGY QUANTIFICATION IN THERMONUCLEAR FUSION REACTIONS OF HYDROGEN ISOTOPES

Eduardo Franzoi
Chemical Engineering, UNIFEBE

Rafaela Bohaczuk Venturelli Knop
Chemical Engineering, UNIFEBE

Abstract: Energy development is an extremely important factor in ensuring the sustainability and economic development of a country. The search for sustainable and renewable sources of energy has been investigated over the years to meet the global energy demand in order to reduce the impacts generated by the burning of fossil fuels. The advancement of civilization requires a vast amount of energy applied to the most diverse ends. Even having risk characteristics that go beyond the generation of fossil fuels, nuclear thermoelectric plants become a means of meeting energy demands taking into account their efficiency. As much as the use of nuclear technology arouses aversion in a large part of society due to accidents in thermonuclear plants, the word radioactivity is still feared by a large part of the global population. The present work aims to study the principles of nuclear energy generation through fission and fusion, dynamically approaching their reactions and quantifying their kinetic energy.
Keywords: Reactor. Fusion. Energy. Fission.

INTRODUCTION

Energy can be considered one of the main constituents of modern society, whether in mechanical, kinetic, thermal, electrical, chemical or nuclear form, it accompanies us everywhere, making technological growth possible by directly intervening in people's lives. al., 2010).

The search for different energy sources has been developed on an ever-increasing scale. One of the goals of the 21st century is to replace traditional energy sources such as coal and oil with renewable and sustainable sources. The use of these sources was not limited to the economic and political scope, but the preservation of nature, bringing new ideas in opposition to the environmental impact caused by fossil fuels.

Currently, the search for new energy sources has been studied and applied on an ever-increasing scale. Gradually replacing traditional sources, such as coal and oil, which tend to become increasingly scarce and expensive, with natural sources that are abundant and inexhaustible for energy generation, is one of the goals of the 21st century. The advantage of using energy from renewable sources is not limited to the economic and political scope, it also focuses, with the same importance, on the preservation of nature as opposed to the environmental impact caused by fossil fuels.

To meet the energy demand, the use of energy sources considered "clean" that have a smaller contribution to the emission of gases that make up the greenhouse effect is increasingly sought. Nuclear energy is a source of electrical energy that can contribute to this change as it has the advantage of not emitting substances that contribute to global warming. (SAPUNARU et al., 2014)

Nuclear technology was first applied during World War II and, like other technologies used in warfare, received a use after it ended. Giving rise to the use of thermonuclear energy generation, with the emergence of the first electric core plants in the 1950s (MARCIAL, 2006; HINRICHS et al., 2010).

In the face of so many discussions related to nuclear energy, the present research aims to expose methods of energy extraction through nuclear fission and fusion, analyzing their risks to nature and humanity and quantifying the energy released by the nuclear fusion process.

THEORETICAL REFERENCE

The Atomistic Theory was first built in the fifth century BC by the philosophers Democritus and Leucippus, who defined the atom as a solid and indivisible particle.

In 1808 John Dalton proposed the theory of the atomic model based on the theory of Democritus and Leucippus, defining atom as homogeneous and indivisible particles that would give rise to known substances.

In the year 1897, JJ Thomson observed the importance of the electron in the constitution of the atom, which at the time were considered as forming elements of matter. Thomson proposed that the atom was formed by a paste called a nucleus with a positive charge and that the electrons would be evenly distributed within the paste. Later this model was refuted by E. Rutherford.

The discovery of the atomic nucleus by the New Zealand physicist Ernest Rutherford, at the beginning of the 20th century, was the starting point of Nuclear Physics. A series of experiments in which beams of particles, composed of neutrons, protons and others, were forced to collide with a nucleus were carried out in order to study the atomic structure and generate artificial elements through nuclear transmutation. Rutherford used an element that emitted positively charged particles to collide with a thin gold plate arranged perpendicular to the alpha particle beam (α) according to figure 1.

Niels Bohr continued the studies of Rutherford's atomic model, where in 1913 he discovered that by increasing the energy of the electrons it moved away from the nucleus, which for Rutherford the same process of increasing energy would cause the electrons to emit electromagnetic waves resulting in the collision with the atomic nucleus.

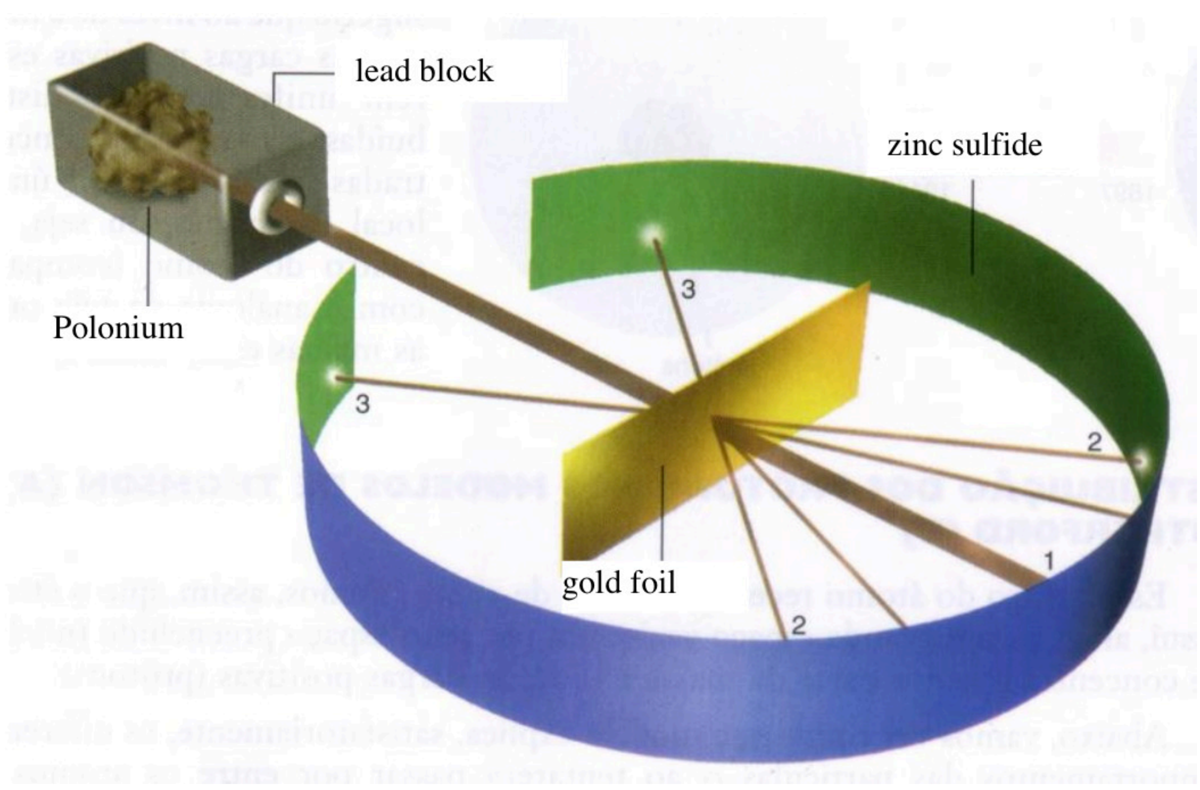

Figure 1: Rutherford's Experiment.

Source: feniana chemistry 2012.

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METHODOLOGICAL PROCEDURES

The phenomenon of nuclear fission was only observed in 1938 by Otto Hahn and Fritz Strassmann in an experiment that consisted of firing neutrons at uranium nuclei in an attempt to produce a nucleus of greater mass. However, the formation of elements with half the mass of uranium was verified.

In 1942 Enrico Fermi verified that the fission of uranium nuclei released neutrons that started other fissions giving rise to a self-sustaining chain reaction.

Nuclear fission consists of a reaction where a heavy nucleus is split giving rise to two or more new elements with masses of the same magnitude. As a result, it causes the release of energy, neutron emission and gamma radiation along with nuclear fragments. (RIBEIRO, 2014)

The apparent ease of carrying out the nuclear fission process is essentially due to the electrically neutral particle that triggers the neutron which, due to the absence of electrical charge, is subject to the electric field of the positively charged nucleus. Which explains the easier approach to the nucleus than a proton.

As the protons present in the nucleus do not have an electrical charge, their quantity can be varied, giving rise to atoms with the same number of protons and different numbers of neutrons. Uranium is present in nature in the form of 3 isotopes. They are: U-238 with 16 neutrons in the nucleus (99.3%), U-235 with 143 neutrons (0.7%) and U-234 with 142 neutrons (negligible amount).

The nuclear fission reaction of uranium-235 results in 2 smaller nuclei and 2 to 3 neutrals as a consequence of the neutron absorption that caused thefission. Therefore, the neutrons released from the result of the first collision can collide with new uranium-235 nuclei, thus generating a chain reaction as shown in figure 2.

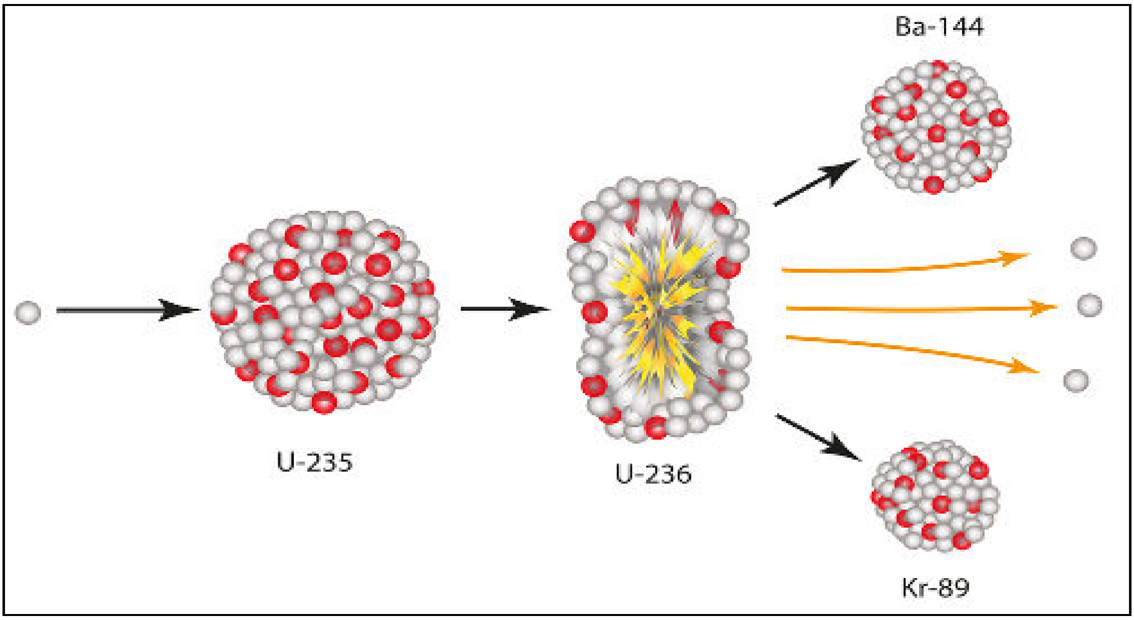

Figure 2: Uranium 235 fission reaction.

Source:Future of Life Institute (2016).

Notice that the reaction in Figure 1 of uranium-235 fissioned by the neutron gave rise to barium-144, krypton-98 and three neutrons that will collide again with uranium-235.

The writing of the nuclear fission reaction equation obeys two specific rules, they are:

- Rule Z: The sum of the atomic numbers, Z, of the reacting particles is equal to the sum of the atomic numbers of the reaction products;
- Rule A: The sum of the mass numbers, A, of the reacting particles is equal to the sum of the mass numbers of the products of the reaction.

The most well-known nuclear fission reaction is the fission of a uranium-235 nucleus that is split into different isotopes represented by the following reaction.

$$^{235}_{92}U + \, ^{1}_{0}n \rightarrow \, ^{142}_{56}Ba + \, ^{91}_{36}Kr + 3\,^{1}_{0}n + \, energia_{MeV}$$

The energy release involved in the process is expressed in MeV per atom instead of kJ/mol, which clarifies the huge difference between the units of magnitude of the energies involved in chemical and nuclear reactions.

As the uranium-235 fission process ends up releasing a lot of energy when the neutron is absorbed by the uranium-235 nucleus, the control of the rational environment occurs in only one way, which is the blocking of the fission-causing agent, that is, the neutron because without neutrons available to generate new fissions the reaction ends. Chemical elements such as cadmium and boron have neutron absorption properties inducing uranium-235 not to fission and are inserted between the fuel elements of the reactors as shown in figure 3, known as reaction control bars.

As the amount of uranium-235 is limited to 0.7% of all uranium present in nature, the fission reaction must be carried out with uranium-238 because in every 1000 atoms of uranium-993 are uranium-235 and 7 are uranium- 235. Even though it contains less than 1% of uranium-235 in nature, it cannot be completely replaced by uranium-238.

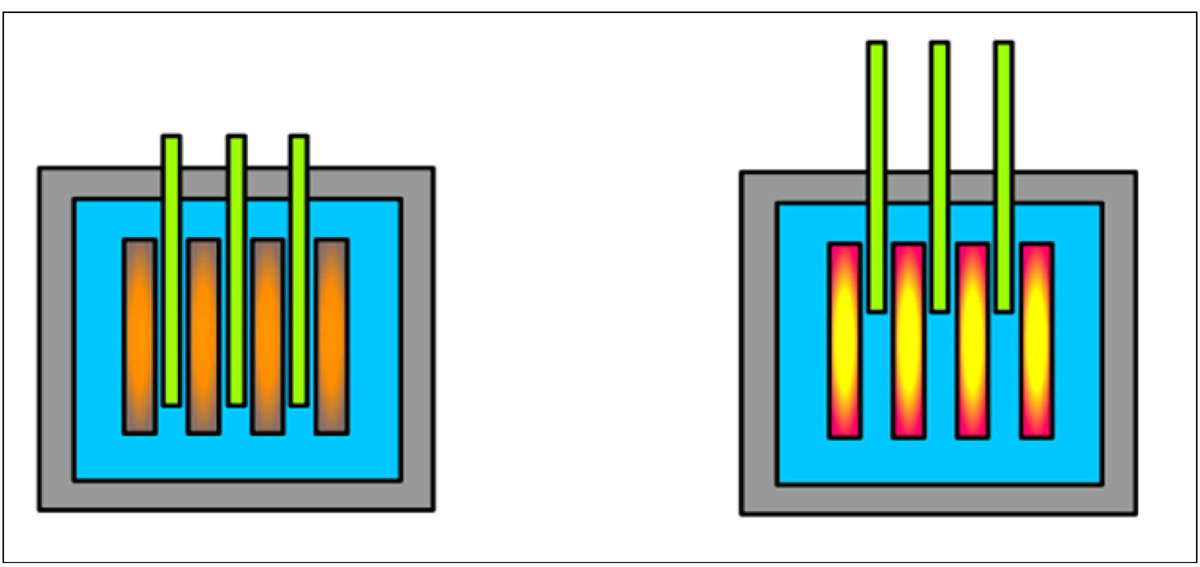

Figure 3: Operation of reaction control bars.

Source: The author (2019).

To start the fission reaction, a minimum amount of uranium-235 is needed, which is easily fissioned by thermal neutrons called "slow". In pressurized water nuclear reactors (PWR) such as the Angra reactors, they need a minimum amount of 3.2% of uranium-235 atoms, that is, for every 1000 uranium atoms, 32 are uranium-235 and 968 are of uranium-238.

In nature, uranium is found with only 0.7% of U-235 isotopes, so it is necessary to carry out an enrichment process so that it can be used in PWR reactors.

The construction of nuclear power plants involves a series of processes to ensure safety, from the design phase to final construction, as well as equipment assembly and correct operation.

In Brazil, two reactorsnuclear PWR (Pressurize Water Reactor) operating under pressurized water are in operation and a third one under construction located in the city of Angra dos Reis, the disposal of equipment as well as the flow of heat exchange for energy generation can be schematized as shown in figure 4.

The reactor fuel is 3.2% concentrated uranium-235 that is inserted into four-meter-long rods mounted in bundles bearing the name of fuel element (figure 2). The rods are manufactured from a special zirconium alloy and, after being inserted, the uranium pellets

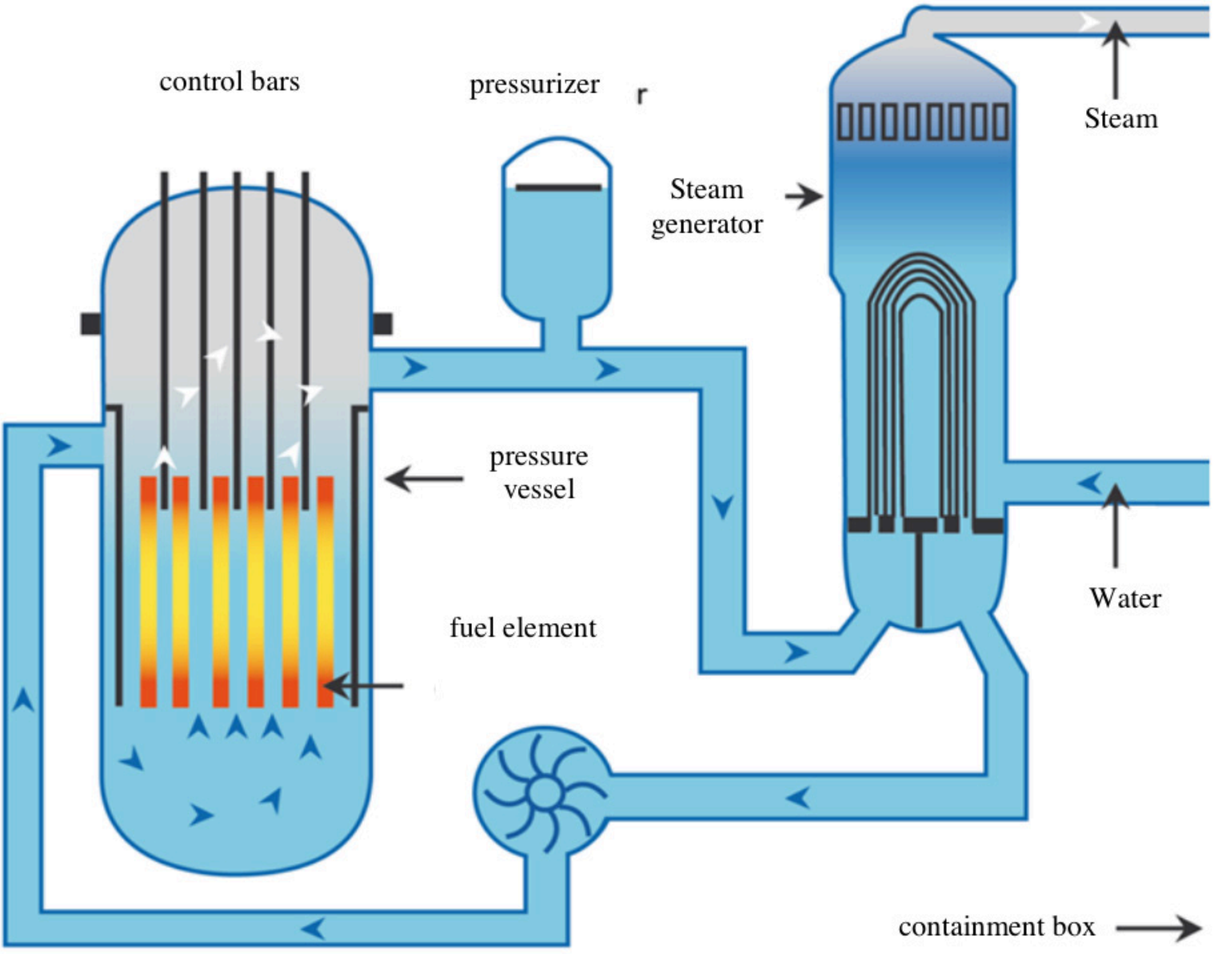

Figure 4: Pressurized water reactor.
World Nuclear Association (adapted) 2012.

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are sealed, making these rods the first physical protection barrier, preventing the exit of radioactive materials into the environment.

The fuel element is inserted into a large vessel capable of withstanding great pressures, the walls of the vessel in Angra1 are about 20 cm and in Angra 2 25 cm, this being the second physical barrier of protection.

As uranium releases energy in the form of heat, it is necessary to install steam generators to capture the thermal energy from nuclear fission, to generate steam pressure to drive the turbines.

Both the steam generator and the reactor pressure vessel are installed inside a large 3.8 cm thick containment box. In Angra 1 the containment has the shape of a cylindrical tube and in Angra 2, it has a spherical shape being the third physical protection barrier.

To ensure greater safety a fourth safety barrier is inserted, the reactor building itself is also designed to ensure that there is no leakage of radioactive material to the outside. Being constructed of concrete and steel, the reactor building has the ability to withstand explosions and plane crashes.

PWR type reactors operate with three independent water systems, they are: primary, secondary and tertiary. In the primary system, water is pumped directly into the reactor core, passing between the fuel element and control bars without coming into contact with the secondary system.

In the secondary system, the water is pumped to the steam generator where it exchanges heat with the primary circuit by thermal conduction, generating the steam that feeds the electricity generating turbines, both the primary system and the secondary system, in addition to being independent, perform a cycle of refrigeration and for working with great pressures are also protected by the third physical barrier of protection.

The independence of the primary and secondary circuits aims to protect the leakage of radioactive matter in case it damages a rod that contains the fuel element, only the primary circuit will have contaminated water. The tertiary circuit finally performs the condensation of the secondary circuit causing the cold water to return to exchange heat with the primary circuit inside the steam generator. It is worth mentioning that the tertiary circuit is completely free of radioactive contaminants and is the only open cooling system where fluid replenishment is constant.

In the design of a nuclear fission plant, several accidents that can occur in the nuclear reactor are imagined, as well as the way to circumvent them, by human action or, by automatic intervention of safety systems, designed for this purpose. The consequences in relation to the equipment, the internal structure of the reactor and, mainly, in relation to the environment are also evaluated. (CARDOSO, IN 2012).

The danger contained in the operation of thermonuclear reactors is directly represented by the radioactivity of the products from the fission of uranium and its release into the environment. The protection barriers have the function of protecting the reactor environment, constituting a passive safety system functioning independently of any action.

The safety philosophy of nuclear fission reactors is written in the sense that nuclear power plants are designed, built and operated with the highest levels of safety and technology available (CARDOSO, EM 2012).

NUCLEAR FUSION REACTORS

Nuclear fusion occurs in stars when the nuclei of hydrogen, in the form of gas, are compressed by gravity reaching temperatures above 14 million degrees. To do the same process on Earth, you need to confine this electrically charged gas (plasma) using magnetic fields generated by machines called tokamaks and heat it up.On land, the fuel for the reactors would be two isotopes of hydrogen: deuterium, which can be extracted from seawater; and tritium, produced from lithium nuclei.

Nuclear fusion entered the imagination and common sense as a myth in the 1980s, when two scientists - Stanley Pons, in the USA, and MartinFleischmann, UK - claimed to have reached fusion at room temperature (WNA, 2012). The announcement of cold fusion was published in 1989 in the journal Nature (JONES et al., 1989) and involved heavy water electrolysis using palladium electrodes causing the deuterium nucleus to reach the melting point at a very high density.

The nuclear fusion process that uses stable isotopes of hydrogen as fuel consists of the union of two light atoms forming a third atom with greater mass and energy. To start the fusion process, the nuclei that will collide must have an initial kinetic energy sufficient to break the barrier.coulomb energy caused by the strong nuclear energy that holds the protons and neutrons together in the atomic nucleus.

Nuclear fusion can occur in two ways, namely: inertial and magnetic confinement. The inertial confinement process involves laser compression of a small sample of hydrogen isotopes.The beam heats the outer layer of the deuterium and tritium solution which, when exploding, generates a compression movement that heats the inner layers of the capsule, reaching a thousand times its liquid density, creating the conditions for fusion. The released energy heats the fuel, generating a chain reaction as the reaction spreads through the fuel. The reaction time is limited by the fuel and lasts less than a microsecond (WNA, 2012).

In the magnetic confinement process, Tokamak reactors are used that generate a toroidal electromagnetic field to suspend, compress and accelerate stable isotopes of hydrogen forming an ionized gas (plasma) causing the atoms to fusion.

RESULTS AND DISCUSSIONS

The Joint European Torus (JET), which is the largest operating tokamak in the world today, produced its first plasma in 1983 and became the first experiment to produce electricity from controlled fusion in 1991, generating 16 MW with a Q performance. of 0.65. Europeans expect that the next generation of machines to be used in the large-scale scientific project, the International Thermonuclear Experimental Reactor (ITER), seeks Q = 10 while future reactions can reach values of Q = 40-50 (EURATOM, 2007). Where:

$$Q = \frac{electricity\ produced\ by\ fusion}{heat\ applied\ to\ plasma}$$

To calculate the energy released in the hydrogen isotope fusion equation it is necessary to calculate the nuclear binding energy which is the energy that must be supplied to the nucleus to separate its protons and neutrons an infinite distance, this relationship was given by Einstein in 1905 by the equation:

$$E = mc^2$$

Einstein demonstrated what was already being verified by a multitude of experiments. It means that if a system gains an amount of energy "E", its mass increases by an amount given by E/c^2. in this context "c" represents the speed of light in vacuum, "E" the binding energy formed by "Z" protons and (A'-Z) neutrons of mass M (Z, A), one can write:

$$Zm_{próton} + (A - Z)m_{nêutron} - M(Z,A) + \frac{E_{connexion}}{c^2}$$

Where:
m_p = mass of the proton
m_N = neutron mass
The binding energy can be described as:

$$E_{connexion} = \left[Zm_{próton} + (A,Z)m_{nêutron} - M(Z,A)\right] * c^2$$

To calculate the binding energy of deuterium and tritium it is necessary to quantify the atomic mass unit (a) of the products and reactants that formed it according to the following reaction:

$$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_0n + Energy_{MeV}$$

where we have:
$1u.m.a$ = 1,66054 x 10^{-27}kg
^1_0n (neutron) = 1.00866 a
^2_1H (deuterium) = 2.01410 a
^3_1H (tritium)= 3.01605 a
(helium) = 4.0026 a ^4_2H

Initially, the mass difference between the sum of the masses of the products and the reactants must be calculated, where we obtain:

$$\delta m = \left[Zm_{próton} + (A,Z)m_{nêutron} - M(Z,A)\right]$$

$$\delta m = [(2{,}01410 + 3{,}01605) - (4{,}0026 + 1{,}00866]$$

$$\delta m = 0{,}01889\ u.m.a.$$

The mass difference between the reactants and products of the deuterium and tritium reaction can be quantified in energy units according to the following equation:

$$Energy = 0{,}01889 * \frac{1{,}66054 * 10^{-27}kg}{1u.m.a.} * \left(299.792{,}458\frac{m}{s}\right)^2 * \frac{1eV}{1{,}602x10^{-19}}$$

$$Energy = 17{,}597873MeV$$

Comparing the fission reaction of uranium with that of the combustion of propane gas, it can be seen that the gas emits 2220J of energy for each mole. Dividing the energy by Avogadro's constant we get:

$$\frac{2220J/mol}{6{,}02x10^{23}molecules/mol} = 3{,}68x10^{-21}J/propane\ molecule$$

Converting the 200 megaelectron volt energy released in the nuclear fission reaction of uranium-235 fissioned by a proton we have:

$$1MeV = 1{,}60218x10^{-13}J$$

$$1{,}60218x10^{-13}x\ 200 = 3{,}20x10^{-11}J/uranium\ atom$$

Dividing the thermal energy contained in the fission of a uranium-235 atom by the thermal energy of burning propane gas we have:

$$\frac{3{,}20x10^{-11}}{3{,}68x10^{-21}} = 8{,}69x10^9$$

It can be seen that the thermal energy released in the fission of a uranium-235 atom is 8.69 billion times greater than the energy released by the combustion of a molecule of propane gas. When analyzing the energy released by the nuclear fusion of the isotopes, deuterium and tritium of 17.6 Megaelectron-volt generate a molar mass of 5.03g/mol.

By dividing the molar mass of U235 by the mass of the reaction of deuterium and tritium, I realized that the molar mass of the fusion reaction is 46.72 less than that of the fission of U235 uranium. Multiplying this value by the energy of 17.6 Megaelectron-voll we have a proportionality of energy release in relation to the molar mass of the elements, being that the nuclear fission of 200 Megaelectron-volt requires 235g/mol and the same mass of deuterium and tritium generates 821.8 Megaelectron-volt totaling 4 times more energy.

FINAL CONSIDERATIONS

The most desired application of nuclear fusion lies in the construction of thermonuclear fusion reactors and despite the immense global effort, controlled nuclear fusion has not yet been achieved, due to the loss of thermal energy in the conditions necessary to carry out fusion is still very high.

The possibility of using nuclear fusion processes to obtain energy, shows promise for a relatively near future in the generation of clean and unlimited electricity from a practical point of view, since it presents minimal risks to the environment when compared to the processes of obtaining energy from nuclear fission.

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