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Nuclear Fusion-A Colossal Energy Source

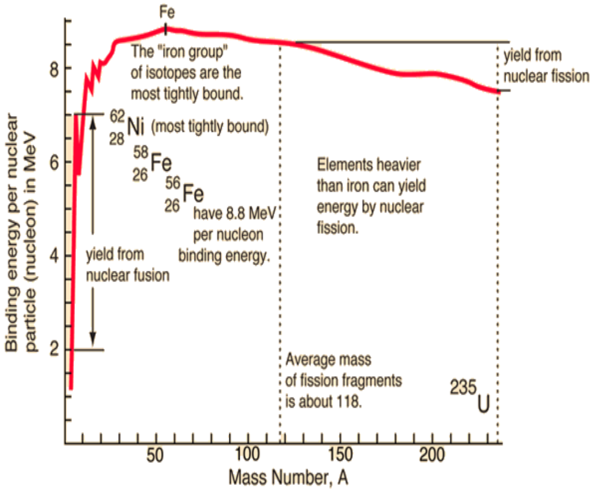
Snehashis Das[1], Shamik Chattaraj[2], Anjana Sengupta[3], Kaustav Mallick[4]
[1, 2, 3, 4]Electrical Engineering, Technique Polytechnic Institute, Hooghly, West Bengal, India-712102
Email address: [1]snnehashis@gmail.com

Abstract**—** With the fast depletion of all other conventional forms of energy resources, it became very much essential to opt for alternative that will be abundant enough to last for quite an effective period of time. Lately, a lot of experimentation and projects are being undertaken to implement nuclear fusion to serve the above purpose. We are familiar with the term nuclear fission i.e. heavier elements breaking down into smaller particles releasing energy; whereas Nuclear Fusion is a phenomenon reverse of fission i.e. lighter elements unites to form heavier elements with release of energy of much greater magnitude compared to fission. In the process of fusion, the Coulomb's Forces are much lesser compared to the binding energy of the resulting nuclei. The very first baby step towards research on fusion began in the year 1929. Building upon the nuclear transmutation experiments by Ernest Rutherford, carried out several years earlier, the laboratory fusion of hydrogen isotopes was first accomplished by Mark Oliphant in 1932. Later on, during Manhattan Project (1940), the concept of fusion was thought for the first time for military purpose, and many other followed after. Research for civil purpose began only in 1950s through thermonuclear fusion. Two projects, the National Ignition Facility and ITER were proposed for the purpose. Designs such as ICF & TOKAMAK are the mega sized reactors upon which world are looking forward to. Although a German company named Lockheed Martin has begun investigating a highly classified reactor of about 100MW (much smaller in size compared to TOKAMAK), its result are yet to be seen. What we need to make a summary about is how well this method (Nuclear fusion) can be used to explore the enormous amount of energy it can produce& what are the measures taken for this purpose.

Keywords**—** Nuclear fusion; nuclear fission; coulomb's forces; binding energy; manhattan project; ITER; TOKAMAK.

I. INTRODUCTION

Nuclear fusion according to nuclear physics is a nuclear reaction in which two or more atomic nuclei collide at a very high speed and unite to form a new type of atomic nucleus. During this process, matter is not conserved because some of the matter of the fusing nuclei is converted to photons (energy). For two nuclei to fuse, they must come close enough to overcome coulomb's forces. If the combined nuclear mass is less than that of iron at the peak of the binding energy curve, then the nuclear particles will be more forcefully bound than they were in the lighter nuclei, and that decrease in mass comes off in the form of energy according to the Einstein's theory of mass defect, for elements heavier than iron, fission will yield energy. It has been found that fusion of one deuteron and one triton releases as much as 17.6 MeV of energy. [2]



II. USEFULNESS OF FUSION ENERGY

We all are aware of the abnormal diminish of orthodox sources of energies in near future. The most important reason that is turning our attention to this type of energy is its tempting amount of energy obtainable compared to very little quantity of input. Moreover the process is pollution free.

III. REQUIREMENTS OF A NUCLEAR FUSION REACTION

The fusion of two nuclei with lower masses than iron (which, along with nickel, has the largest binding energy per nucleon) generally releases energy, while the fusion of nuclei heavier than iron absorbs energy (thus reverse happens in fission). The reason of the energy released in fusion of light elements is because of the interaction of two opposing forces, the nuclear force which combines together protons and neutrons, and the Coulomb force which causes protons to repel each other. The protons are positively charged and repel each other but they nonetheless stick together, demonstrating the existence of another force referred to as nuclear attraction. This force, called the strong nuclear force, overcomes electric repulsion in a very close range. The effect of this force is not observed outside the nucleus; hence the force has a strong dependence on distance, making it a short-range force. The same force also pulls the neutrons together, or neutrons and protons together. Since the nuclear force is stronger than the Coulomb force for atomic nuclei smaller than iron and nickel, building up these nuclei from lighter nuclei by fusion releases the extra energy from the net attraction of these particles. For heavier nuclei, however, no energy is released, since the nuclear force is short-range and discontinues acting across still larger atomic nuclei. Thus, energy is no longer released when such nuclei are made by fusion; instead, energy is absorbed in

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such processes. High temperature is vital to sustain a reaction and this is the reason such reactions are often called Thermonuclear Reactions [3].

IV. FUSION REACTORS

Reactors for nuclear fusion are of two main types, confinement reactors and inertial confinement reactors. The strategies for creating fusion reactors are dependent on the fact that the temperatures involved in nuclear fusion are extremely high to be restricted in any material container.

The strategy of the magnetic confinement reactor is to confine the hot plasma by means of magnetic fields which keep it continually in looping paths which do not touch the wall of the container. This is typified by the Tokamak design, the most famous example of which is the TFTR at Princeton. In magnetic confinement fusion, hundreds of cubic metres of D-T plasma at a density of less than a milligram per cubic metres are confined by a magnetic field at a few atmospheres pressure and heated up to its fusion temperature.

Magnetic fields are ideal for confining plasma because the electrical charges on the separated ions and electrons mean that they follow the magnetic field lines. The aim is to prevent the particles from coming into contact with the reactor walls as this will dissipate their heat and slow them down. The most effective magnetic configuration is toroidal, shaped like a doughnut, in which the magnetic field is curved around to form aclosed loop. For proper confinement, this toroidal field must have superimposed upon it a perpendicular field component (a poloidal field). The result is a magnetic field with force lines following spiral (helical) paths that confine and control the plasma [4].

There are several types of toroidal confinement system, the most important being tokamaks, stellarators and reversed field pinch (RFP) devices.

In a tokamak, the toroidal field is created by a series of coils evenly spaced around the torus-shaped reactor, and the poloidal field is created by a system of horizontal coils outside the toroidal magnet structure. A strong electric current is induced in the plasma using a central solenoid, and this induced current also contributes to the poloidal field. In a stellarator, the helical lines of force are produced by a series of coils which may themselves be helical in shape. Unlike tokamaks, stellarators do not require a toroidal current to be induced in the plasma. RFP devices have the same toroidal and poloidal components as a tokamak, but the current flowing through the plasma is much stronger and the direction of the toroidal field within the plasma is reversed.

In tokamaks and RFP devices, the current flowing through the plasma also serves to heat it to a temperature of about 10 million degrees Celsius. Beyond that, additional heating systems are needed to achieve the temperatures necessary for fusion. In stellarators, these heating systems have to supply all the energy needed.

The tokamak (“*toroidalnyakameraeemagnetnayakatushka*”– torus-shaped magnetic chamber) was designed in 1951 by Soviet physicists Andrei Sakharov and Igor Tamm. Tokamaks operate within limited parameters outside which sudden losses of energy confinement (disruptions) can occur, causing major thermal and mechanical stresses to the structure and walls. Nevertheless, it is considered the most promising design, and research is continuing on various tokamaks around the world.

Research is also being carried out on several types of stellarator. Lyman Spitzer devised and began work on the first fusion device – a stellarator – at the Princeton Plasma Physics Laboratory in 1951. Due to the difficulty in confining plasmas, stellarators fell out of favor until computer modeling techniques allowed accurate geometries to be calculated. Because stellarators have no toroidal plasma current, plasma stability is increased compared with tokamaks. Since the burning plasma can be more easily controlled and monitored, stellarators have an intrinsic potential for steady-state, continuous operation. The disadvantage is that, due to their more complex shape, stellarators are much more complex than tokamaks to design and build.

RFP devices differ from tokamaks mainly in the spatial distribution of the toroidal magnetic field, which changes sign at the edge of the plasma. The RFX machine in Padua, Italy is used to study the physical problems arising from the spontaneous reorganization of the magnetic field, which is an intrinsic feature of this configuration.

The strategy of the inertial confinement reactor is to put such high energy density into a small pellet of deuterium-tritium that it fuses in such a short time that it can't move appreciably. The most advanced test reactors involve laser fusion, particularly in the Shiva and Nova reactors at Lawrence Livermore Laboratories. In inertial confinement fusion, which is a newer line of research, laser or ion beams are focused very precisely onto the surface of a target, which is a pellet of D-T fuel, a few millimeters in diameter. This heats the outer layer of the material, which explodes outwards generating an inward-moving compression front or implosion that compresses and heats the inner layers of material. The core of the fuel may be compressed to one thousand times its liquid density, resulting in conditions where fusion can occur. The energy released then would heat the surrounding fuel, which may also undergo fusion leading to a chain reaction (known as ignition) as the reaction spreads outwards through the fuel. The time required for these reactions to occur is limited by the inertia of the fuel (hence the name), but is less than a microsecond. So far, most inertial confinement work has involved lasers.

Recent work at Osaka University's Institute of Laser Engineering in Japan suggests that ignition may be achieved at lower temperature with a second very intense laser pulse guided through a millimeter-high gold cone into the compressed fuel, and timed to coincide with the peak compression. This technique, known as 'fast ignition', means that fuel compression is separated from hot spot generation with ignition, making the process more practical [1].

V. THE PROCESS OF FUSION

A. *Confinement Time for Fusion*

Confinement time in nuclear fusion devices is defined as the time the plasma is maintained at a temperature above the critical ignition temperature. To yield more energy from the fusion than has been invested to heat the plasma, the plasma must be held up to this temperature for some minimum length of time. Calculations of that minimum time are

TABLE I. Time of heating of plasma.

Time of Plasma Confinement	Type of Fusion
$\tau = \frac{2 \times 10^{14}}{n}\ s$	Deuterium-tritium fusion
$\tau = \frac{5 \times 10^{15}}{n}\ s$	Deuterium-deuterium fusion

Where n is the ion density in the plasma. The product of the ion density and confinement time required for fusion is called Lawson's criterion.

B. *Ion Density for Fusion*

Even given a high enough temperature to overcome the coulomb barrier to nuclear fusion, a critical density of ions must be maintained to make the probability of collision high enough to achieve a net yield of energy from the reaction. The density required for a net energy yield is correlated with the confinement time for the hot plasma, so the minimum condition for a productive fusion reaction is typically stated in terms of the product of the ion density and confinement time, called Lawson's criterion. The calculated values are [5].

TABLE II. Lawson's Criterion Values for different fusions.

Lawson's Criterion Value	Type of Fusion
$n\tau = 2 \times 10^{14}\ s/cm^3$	Deuterium-tritium fusion
$n\tau = 5 \times 10^{15}\ s/cm^3$	Deuterium-deuterium fusion

VI. ENERGY RELEASED DURING FUSION

A. *Deuterium Cycle of Fusion*

The four fusion reactions which can occur with deuterium can be considered to form a deuterium cycle. The four reactions:

$$ {}_1^2H + {}_1^2H \rightarrow {}_2^3He + {}_0^1n + 3.27MeV $$

$$ {}_1^2H + {}_1^2H \rightarrow {}_1^3H + {}_1^1H + 4.03MeV $$

$$ {}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n + 17.59MeV $$

$$ {}_1^2H + {}_2^3He \rightarrow {}_2^4He + {}_1^1H + 18.3MeV $$

Above reactions can be combined as

$$ 6\,{}_1^2H + {}_1^3H + {}_2^3He \rightarrow 2\,{}_2^4He + {}_2^3He + {}_1^3H + 2\,{}_1^1H + 2\,{}_0^1n + 43.2MeV $$

or, omitting those constituents whose concentrations do not change:

$$ 6\,{}_1^2H \rightarrow 2\,{}_2^4He + 2\,{}_1^1H + 2\,{}_0^1n + 43.2MeV $$

This enormous amount of energy can be used to do useful work when we are living in a time where we need to think where we will land up after a decade with the limited sources of energy left.

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