FUSION ENERGY HARNESSING, REACTOR TECHNOLOGY, AND SUSTAINABILITY

Flavio Dobran
GVES, New York, U.S.A

Abstract

The energy produced from the controlled thermonuclear fusion of hydrogen isotopes can replace fossil fuels and become a sustainable energy source. The fusion of deuterium and tritium has been achieved in several experimental reactors where the plasmas are confined with magnetic fields and there is high optimism that this will also be achieved with laser and ion beams. The plasma confinements and reactor

Kirk-Othmer Encyclopedia of Chemical Technology.
DOI: 10.1002/0471238961.0621190905121209.a01.pub2

technologies of tokamaks and stellarators are paving the way for building demonstration fusion reactors and subsequently commercial fusion power plants. Following a review of the magnetic and inertial plasma confinement concepts, the reactor technologies that implement these concepts are assessed for producing sustained plasma ignition, external plasma heating, control of plasma instabilities, developments of low-activation and high strength materials, coolants for removing fusion energy from the reactor, and breeding tritium in the blanket of the reactor for achieving fuel self-sufficiency. Sustainability of fusion energy requires the long-term availability of fusion fuels and reactor components materials, social acceptability, minimization of waste products, and safe operation of fusion power plants. These and other issues considered strongly suggest that the fusion energy will become a viable energy source for human development.

Keywords: fusion energy; fusion reactions; fusion reactor technology; magnetic confinement fusion; plasma confinement.

1. Introduction

The world's population is projected to increase from 7 billion people today to 9 billion people by the end of this century (1) and the current power demand of 12 TW is expected to double during the following decades (2). About 80% of the current energy needs are being supplied by fossil fuels (oil, gas, coal) and within 100 years this resource will be severely depleted. These energy sources currently emit some 40 $GtCO_2e$ per year of greenhouse gases into the atmosphere, warm the earth's climate system, melt glaciers and produce sea level rise, and have the potential to uproot hundreds of millions of people (3). Harvesting the required energy with solar thermal, wind, photovoltaic, and biomass energy conversion systems from the 10^5 TW of power delivered by the Sun to our planet would require the development of new energy supply technologies, overcoming security issues of energy production and distribution, and satisfying the social constraints posed by various cultures with different resources and aspirations.

The energy extracted with solar thermal, photovoltaic, wind, and biomass systems have power densities that are 10,000 times smaller than those of fossil fuels and more than 1,000,000 times smaller than those of nuclear energy systems and thus require large investments in infrastructures and constructions in some poorly secured locations to make them viable for producing the bulk of the energy needs of humanity (about 200 quads today). Harvesting of nuclear energy from the splitting of heavy nuclei (uranium, thorium, plutonium) in nuclear fission reactors can produce substantial amounts of base load power, but this energy source is also unsustainable and some products of reactions produce the publicly unacceptable long-lived (millions of years) radioactive products or spent nuclear fuel (4) that we have not yet been able to manage properly. The nuclear fission power generation can triple by 2050 and save the planet some 2 Gt of carbon emissions per year with the new Generation IV reactors that employ safer passive cooling systems (5), but even a thousand of such GW power producing reactors fall short from delivering the expected world's power need beyond 2050 and convincing the public that the accidents such as at Chernobyl and Fukushima can be avoided (6).

When the nuclei of atoms fuse or combine their total mass is reduced and this mass difference is transformed into the energies of the products of the reaction.

The amount of energy released through this process is huge as attested by the man's ability to relinquish this energy through thermonuclear bombs. In the interior of the Sun the protons of hydrogen fuse to produce helium and when the hydrogen is exhausted helium nuclei fuse to produce the next heavier element lithium and so forth. The conversion of just 0.1 g of hydrogen to energy every second is equivalent to the power of 10 TW and therefore here lies the great interest in exploiting this energy for humanity. Fusion energy can qualify as a *sustainable* energy source if it can provide most of the energy needs of the future, can be produced from natural resources that do not exceed the sustainable yield of these resources, be socially acceptable and affordable, and if its emissions do not produce environmental problems and cause public health concerns (7,8).

At the present we do not have an energy source technology that can substitute fossil fuels, but if developed the *controlled nuclear fusion* offers this possibility. Such a technology would not produce long-term radioactive waste, emissions causing global warming and health problems, and nuclear proliferation issues. There are, however, some technological problems that have to be solved before a reliable fusion power can be developed and some sustainability concerns regarding the availability of fusion materials that need to be addressed before the fusion energy can become a *sustainable* energy source.

The principles and methods for harnessing fusion energy are presented in Section 2. In the first generation fusion power reactors, fusion reactions are envisaged to be produced with magnetic and inertial plasma confinement systems. Magnetic confinement fusion employs magnetic fields to confine deuterium and tritium for a sufficient time and at high temperature to make these species interact, and the *breakeven condition* occurs when the energy supplied to achieve fusion is equal to the energy produced from fusion. Several experimental reactors have already achieved this condition. Inertial confinement fusion employs pulses of radiation, particle beams, or electric current to compress the fuel to initiate fusion reactions, but cannot yet claim the breakeven condition success, in spite of considerable investments by several governments to develop this technology to satisfy their nuclear stockpile stewardship programs. The fusion *ignition condition* is achieved when the nuclear fusion reactions become self-sustaining. Because this is more difficult to achieve than breakeven, different technologies are being developed for this purpose. The successes of research projects are crucial for building demonstration fusion reactors by the middle of this century, and if this is successful for transferring the knowledge base to the industry for building commercial fusion power plants during the second half of the twenty-first century (Section 3). Power producing fusion reactors will be technologically complex machines and in Section 4 we will address the sustainability issues of fusion in order to assess the prospects of fusion energy to become a viable energy source. We will conclude that although we do not yet possess all of the technologies for producing fusion power on a commercial scale that these technologies can be developed (and developed rapidly with adequate resources), before we run out of fossil fuels, produce irreparable damage to the environment, and place a significant burden on future generations.

2. Fusion Energy Harnessing

2.1. Fusion Reactions.

Fusion of hydrogen in the Sun produces about 10^{26} W of power and for almost a century the scientists have strived to duplicate this process on the Earth with a wide variety of different methods. The electrons in an atom are held together by the attractive *Coulomb force* between the negatively charged electrons surrounding the nucleus and positively charged protons in the nucleus, and energy is required to ionize or strip the electrons from the nucleus. Protons and neutrons in a nucleus are held together by the attractive short-range nuclear or *strong force* that overcomes the repulsive Coulomb force between the protons at the distances of the size of the nucleus ($1–10\times10^{-15}$ m). For fusion to occur, the reacting nuclei must have sufficient kinetic energies to come close to each other so that the attractive strong force can overcome the repulsive Coulomb force and produce a rearrangement of *nucleons* (protons and neutrons) in a *compound nucleus* with a low potential energy.

A nucleus ${}^{A}_{Z}\mathrm{M}$ (often abbreviated ${}^{A}\mathrm{M}$) is identified with its *mass number A* (number of protons and neutrons, or atomic weight rounded to the nearest whole number), *atomic number Z* (number of protons), and nuclear *rest mass M*. In addition, a nucleus is also characterized by its size, shape, binding energy, angular momentum, and (if it is unstable) *half-life*. The radius of a nucleus is much smaller than that of an atom (10^{-10} m) and the nuclei in some atoms are spherical while in others are stretched into deformed shapes.

Nuclear reactions change the elements or nuclides by altering the energy states of the nuclei. When a nuclide b is made to interact with another nuclide or subatomic particle a the product is usually another nuclide c and light particle d

$$a + b \rightarrow c + d, \tag{1}$$

where a and d may be photons, electrons, protons, neutrons, or other nuclides. Such a reaction requires that the *relativistic total energy E* (comprised of kinetic energy E_{KE} and rest mass energy Mc^2) of reactants is conserved, ie,

$$\sum_{a+b=r} Mc^2 - \sum_{c+d=p} Mc^2 = \sum_{c+d=p} E_{\mathrm{KE}} - \sum_{a+b=r} E_{\mathrm{KE}}, \tag{2}$$

where $c \sim 10^8$ m/s is the speed of light. Here, the subscripts r and p denote the reactants and products, respectively, of the nuclear reaction. The nuclear strong force holding the nucleons together is expressed in terms of the *binding energy B*, defined as

$$B = (Z\,m_{\mathrm{p}} + (A - Z)m_{\mathrm{n}} - M)c^2, \tag{3}$$

where m_{p} is the mass of the proton and m_{n} is the mass of the neutron. The binding energy is the energy required to dissociate a nucleus into its components protons and neutrons and is usually expressed in terms of the average energy per nucleon B/A. The binding energy of nuclei (Fig. 1) grow rapidly with A, reach a maximum around $A = 56$ (${}^{56}_{26}\mathrm{Fe}$) and then decreases slightly for heavier elements. The greater is the stability of a nucleus the greater is its binding energy or the smaller is its potential energy. The nuclei with low masses generally release energy and the nuclei with heavy masses require energy to achieve fusion. The heavy elements in nature are produced when massive stars undergo violent explosions or *supernova nucleosynthesis* where there is an abundance of energy.

The *Q value* of a nuclear reaction is defined as the difference between the rest mass energies of the reactants and the rest mass energies of the products of the reaction, and by equation 3 is equal to the difference between the binding energies

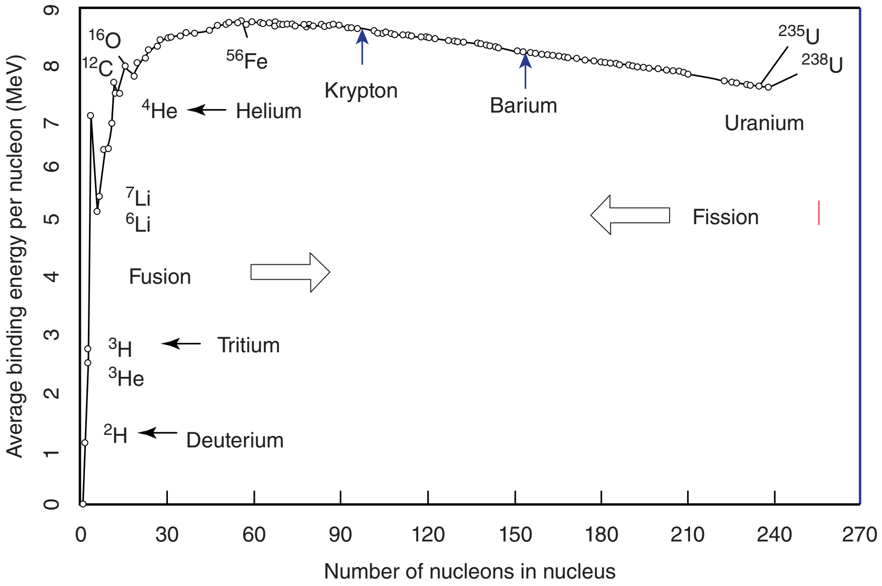


Fig. 1. Average binding energy per nucleon B/A vs the mass number A for the elements from hydrogen nucleus ($Z = 1$ and $B = 0$) to ^{238}U. (Adapted from Reference 9.)

of the products of the reaction and the binding energies of the reactants of the reaction, ie,

$$Q = \left(\sum_r M - \sum_p M \right) c^2 = \sum_p B - \sum_r B \tag{4}$$

where use was made of the conservation of nucleons A and charge Z in the reaction. Fusion reactions with low atomic mass numbers are exothermic ($Q > 0$) because the products have higher binding energies (nucleons are more tightly bound) than the reactants, or the products have a smaller mass than the reactants.

Hydrogen $^{A}_{Z}$H has several *isotopes* (same number of protons Z but different mass number A): $^{1}_{1}$H is the proton p, $^{2}_{1}$H (heavy hydrogen) is the *deuterium* D with one proton and one neutron, and $^{3}_{1}$H is the *tritium* T with one proton and two neutrons. The atoms of these isotopes have one electron to balance the charge of the one proton and thus their chemical properties are similar. The photons produced in nuclear reactions can be *γ-rays* and *X-rays*, and as an example are produced when neutrons interact with protons to produce deuterium, or when a neutron with the half-life of 12 min decays into a proton, an electron, and a neutrino. When D and T combine (Table 1), they produce an *α-particle* or helium nucleus $^{4}_{2}$He with a very large binding energy (Fig. 1) and one free neutron that carries most of the released energy in the form of kinetic energy. On Earth (as opposed to in the stars), we cannot convert $^{1}_{1}$H into energy without inexpensive proton accelerators and instead must employ deuterium and tritium at a sufficiently high temperature to make them react. The helium nucleus is a very stable and harmless byproduct. Deuterium occurs naturally in water as D_2O in one part for every 6400 parts of H_2O and is easy to separate it out (Section 4). Tritium does not occur naturally since it is an unstable isotope with the half-life of 12.3 years

Table 1. **Important Fusion Reactions and Their Q Values and Cross Sections σ at Different Center of Mass Kinetic Energies ε of Reacting Nuclei**

Reaction	Q (MeV)	σ ($\varepsilon = 10$ keV) (barn)	σ ($\varepsilon = 100$ keV) (barn)	$\sigma_{\max}$ (barn)	$\varepsilon_{\max}$ (keV)
Main fuels					
$D + T \rightarrow \alpha$ (3.5 MeV) + n (14.1 MeV)	17.6	2.72×10^{-2}	3.43	5.0	64
$D + D \rightarrow T$ (1.01 MeV) + p (3.03 MeV)	4.04	2.81×10^{-4}	3.3×10^{-2}	0.096	1250
$D + D \rightarrow {}^{3}He$ (0.82 MeV) + n (2.45 MeV)	3.27	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T + T \rightarrow \alpha$ (1.26 MeV) + $2n$ (10.6 MeV)	11.3	7.9×10^{-4}	3.4×10^{-2}	0.16	1000
Advanced fuels					
$D + {}^{3}He \rightarrow \alpha$ (3.67 MeV) + p (14.67 MeV)	18.3	2.2×10^{-7}	1.0×10^{-1}	0.9	250
$p + {}^{6}Li \rightarrow \alpha$ (1.7 MeV) + ${}^{3}He$ (2.3 MeV)	4.0	6.0×10^{-10}	7.0×10^{-3}	0.22	1500
$p + {}^{7}Li \rightarrow 2\alpha$ (22.4 MeV)	17.3				
$p + {}^{11}B \rightarrow 3\alpha$ (8.68 MeV)	8.7	4.6×10^{-17}	3.0×10^{-4}	1.2	550
$p + p \rightarrow D + e^{+} + \nu$	1.44	3.6×10^{-26}	4.4×10^{-25}		
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	1.94	1.9×10^{-26}	2.0×10^{-10}	1.0×10^{-4}	400

Source: Adapted from References 10,11.
1 barn $= 10^{-28}$ m^{2}.
e^{+} is the positron and ν is the neutrino. $\varepsilon_{\max}$ is the center of mass kinetic energy corresponding to $\sigma_{\max}$.

and decays into ${}^{3}_{2}He$ by emitting a high energy electron and a neutrino (*β-decay*). Tritium must be therefore produced externally or internally of a fusion reactor and as we will see this presents some sustainability issues for the first-generation fusion power reactors operating with deuterium and tritium fuels. When two deuterons are used to produce fusion reactions the need for tritium disappears, but these reactions require very high kinetic energies of the reactants before undergoing fusion and are envisaged to be employed in subsequent generations of fusion power plants.

The unit of energy Joule, J, is too big to use for atoms and the more appropriate unit is the electron volt, eV, which is equal to 1.6×10^{-19} J. Molecules are typically held together with energies of 1 eV, the electron in an atom is bound to the nucleus with about 10 eV, a fusion reaction yields about 10 MeV, and a fission reaction produces typically 100 MeV. Mass can be written in *atomic mass units* (amu), which by the Einstein's mass-energy equivalence ($E = \Delta Mc^{2}$) can also be expressed in energy units. Thus, when a proton (1.00728 amu) and a neutron (1.00866 amu) combine to form deuterium (2.01355 amu), the missing mass of 0.00239 amu is equivalent to 2.225 MeV (931.5 MeV/amu) and is carried by the released γ-ray (photon). When, however, the heavier tritium is formed by adding a neutron to deuterium, the amount of released energy is 6.2504 MeV, and this process of binding energy per nucleon continues to grow as protons and neutrons are added to more massive nuclei until a maximum of about 8 MeV per nucleon is reached around $A = 60$ (Fig. 1). The balance between the repulsive Coulomb force between protons and the attractive strong nuclear force between nucleons sets the limit on how large a nucleus can grow.

There are many fusion reactions with $Q > 0$ and the important quantities that characterize these reactions are the fusion *cross section σ* and the *average reactivity*

$<\sigma v>$ of the reaction, where v is the relative speed between the interacting particles. The fusion cross section measures the probability of a pair of particles to fuse and can be expressed in terms of the center of mass kinetic energies of the particles. The averaged reactivity $<\sigma v>$ can then be computed by using the experimentally determined cross section σ and the distribution function *f(v)* of the species' relative velocity v. When the specie j is in thermal equilibrium with other species it has a *Maxwellian or Gaussian distribution* of velocities

$$f_j(v_j) = \left(\frac{m_j}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m_j v_j^2}{2k_\mathrm{B} T}\right), \tag{5}$$

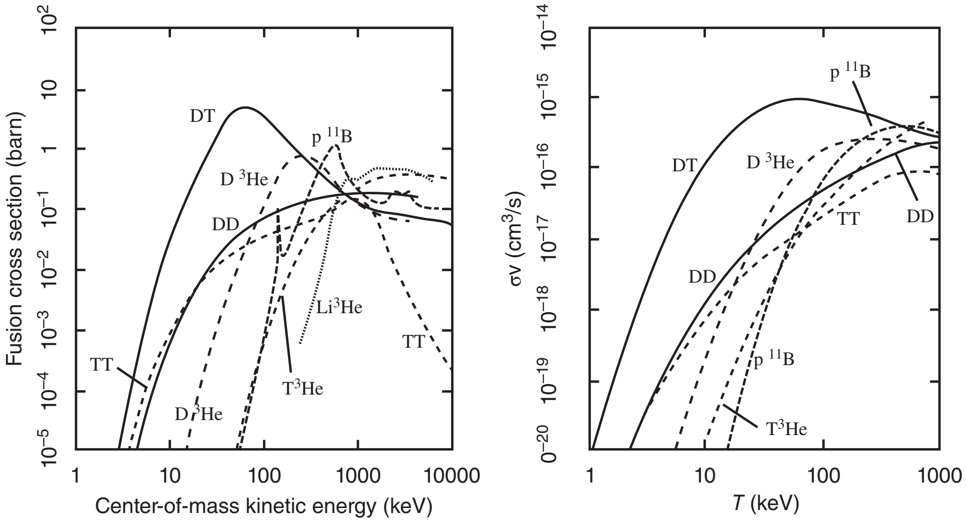
where T is the temperature and k_B is the Boltzmann constant. This distribution function can be used to determine the mean kinetic energy of particles

$$E_{jav} = \frac{\int\limits_{-\infty}^{\infty} \frac{1}{2} m_j v_j^2 f_j(v_j)\mathrm{d}v_j}{\int_{-\infty}^{\infty} f_j(v_j)\mathrm{d}v_j} = \frac{3}{2} k_\mathrm{B} T \tag{6}$$

and since T and E are closely related it is customary in plasma physics to express the temperature in units of energy, where to $1\,\mathrm{eV} = k_\mathrm{B}T$ corresponds the temperature of

$$T = \frac{1.6 \times 10^{-19}}{1.38 \times 10^{-23}} = 11{,}600\,\mathrm{K} \tag{7}$$

The Maxwellian distribution function can be used to determine the average reactivity $<\sigma v>$ of reacting species and Figure 2 illustrates both fusion cross section and reactivity of some important fusion fuels in thermal equilibrium. It



(a) (b)

Fig. 2. (a) Fusion cross section as a function of the center of mass kinetic energy for reactions of interest to controlled fusion. The curve labeled DD accounts for the sum of the two branches of this reaction. (b) Reactivity of some fusion reactions vs the ion temperatures in keV. (Adapted from Reference 12.)

is readily apparent from these data that the reactivity of DT reaction is more than 100 times larger than that of other reactions at 50 keV. The second most probable reaction at energies below 25 keV is the DD reaction, whereas in the energy range 24–250 keV is D^{3}He. Above 250 keV, other reactions (p^{11}B, TT, T^{3}He) become of interest, but they are more difficult to achieve in a controlled manner. Table 1 summarizes the reaction characteristics of the main fusion fuels and some advanced fuels together with their Q values, cross sections at 10 and 100 keV, and the maximum cross sections and energies corresponding to these reactions.

The deuterium–tritium (DT) reaction has the maximum cross section of 5 barn and corresponds to the center of mass kinetic energy of about 64 keV or the ion temperature in excess of 700×10^6 K. To achieve fusion, it is not, however, necessary for particles to have this mean energy, because even at the mean kinetic energy of 10 keV (116×10^6 K) there is already a sufficient number of particles in the *tail* of the velocity distribution function with very large velocities and energies that can penetrate the Coulomb barrier and merge with the particles in the nuclei or produce many fusion reactions. For the DT reaction, the Coulomb barrier is about 400 keV (13) and the quantum mechanical tunneling helps to reduce this energy barrier. A mean energy of 10 keV produces a thermal velocity of about 10^6 m/s for deuterium and 6×10^7 m/s for electrons ($v_{\text{th}} = \sqrt{2T/m}$), and in a reactor of 10 m size these particles can be lost in about 10 μs. This would prevent fusion to occur (see below) and thus suitable methods must be found to confine these particles in the plasma for longer times. The DT reaction produces 17.6 MeV of energy with the α-particle carrying 3.5 and neutron carrying 14.1 MeV of energy. The helium nuclei are stable and if confined for sufficient time heat the plasma and can sustain fusion reactions without supplying external energy. The neutrons carry 80% of the fusion energy and their energies can be captured in the chamber wall surrounding the plasma and transformed into heat for producing electricity (Section 3). The DT reactions do not produce radioactive isotopes directly, but indirectly through the fusion neutrons interacting with the materials surrounding the plasma (fusion chamber and vacuum vessel walls, coils) and when employed to breed tritium in the wall of the chamber or *blanket* of the reactor.

Tritium is radioactive with a short half-life (12.3 years) and thus it does not exist in nature and must be produced for use in DT fusion reactors. Heavy water fission reactors currently produce most of this material (14), but this is not sufficient for fueling the commercial fusion reactors of the future, each of which requires about 10 kg of T inventory to make it functional. Tritium can, however, be produced by allowing the fusion neutrons to interact with lithium, via the reactions

$$n(\text{slow}) + {}^6\text{Li} \rightarrow \text{T} + {}^4\text{He} + 4.8\,\text{MeV} \tag{8}$$

$$n(\text{fast}) + {}^7\text{Li} \rightarrow \text{T} + {}^4\text{He} + n - 2.5\,\text{MeV} \tag{9}$$

where the first reaction with thermal neutrons is exothermic and the second reaction with fast neutrons is endothermic. The seawater contains more than 200 billion tons of lithium (15) and to produce tritium in a fusion reactor use can be made of the fusion neutrons in the blanket containing Li. But these neutrons are not sufficient to produce the required amount of T and *neutron multiplier* materials must be employed to increase their abundance. This process of producing T is called *breeding* and requires the availabilities of Li and neutron multiplying materials such as Be or Pb. The *Tritium Breeding Ratio* (TBR) is defined as

$$\mathrm{TBR} = \frac{\text{tritium production rate in the blanket}}{\text{tritium destruction rate in the plasma core}} \tag{10}$$

In the absence of T from other sources it is necessary to have $\mathrm{TBR} > 1$ in order to compensate for tritium losses during extraction, transfer, and decay before injection into plasma. The upper limit estimates of TBR for various blanket materials range from 0.9 to 2.7 (13) and the reactions of ^{6}Li, ^{7}Li, ^{9}Be, and Pb with neutrons produce large cross sections (0.3–2 bars) (12). D, Li, Be, and Pb, are thus the principal DT fusion fuels that should be *sustainable* for long-term use.

The DD reactions (Table 1) are not completely clean, either, because they also produce neutrons, but these neutrons have an order of magnitude smaller energy than the neutrons of DT reactions and thus produce much less damage when interacting with fusion chamber materials. Since the products T and ^{3}He of DD reactions are fuels in DT and D^{3}He reactions, no radioactive ash or waste is produced in the plasma. The reactions between hydrogen isotopes and light nuclei (He, Li, B) belong to advanced fusion reactions. The D^{3}He reaction has a sizable reactivity at low temperatures and produces no neutrons, but, unfortunately, one cannot prevent deuterium from fusing with itself and produce tritium and neutrons. However, the neutrons produced are of low energy. ^{3}He does not occur naturally and a reactor that uses this fuel requires mining on the moon (16). The proton–boron p^{11}B reaction is particularly attractive because it eliminates the need for blanket shielding, tritium production and recovery, and the remote handling operations. The p^{6}Li and p^{7}Li reactions look attractive in terms of the availability of fuels, but it is very difficult to produce controlled fusion because of their very small cross-sections.

At ordinary temperatures, the atoms and molecules are neutral particles where the negatively charged electrons are bound by the electrical or Coulomb force to the positively charged nuclei. When these particles attain sufficient kinetic energies or temperature the atoms begin to ionize or the electrons and nuclei begin to form a gas of charged and neutral particles. The charged particles generate *local* concentrations of positive ions and negative electrons that generate local electric fields and currents that produce magnetic fields. These fields in turn affect the motions of particles far away and cause the mixture to exhibit a *collective behavior*. If, moreover, the dimension of the system containing these particles is much larger than the Debye distance that characterizes the local concentration of charges (1 μm–1 mm), the mixture is said to be *quasineutral* and such a mixture is technically called *plasma* (17).

2.2. Plasma Confinement.

The particles in a gas at low temperatures are mostly neutral atoms and molecules whereas in a plasma most of the electrons are separated from the nuclei and both can readily respond to electric and magnetic fields. The Sun is a ball of plasma at a temperature of about 20 million degrees (except for the thin outer layer or *photosphere* where the temperature is considerably smaller) where the fusion process proceeds by the interactions of