

# Chapter 6

## Fusion Energy

**Abstract** Fusion is the energy that powers the stars, including our own Sun. Deep in the mass of the stars common hydrogen is converted first to deuterium. Two nuclei of deuterium combine to form helium, while releasing a large amount of energy. Since the fusion reactions were first discovered, it was realized by the scientific community that the controlled harnessing of fusion may provide enough energy to the human society for millions of years. Fusion energy may solve the “energy problem” for humanity. Fusion energy is a panacea whose realization may not be too far in the future. Multinational research and development efforts have produced plasma confining methods, which may lead to continuous and controlled fusion during the twenty-first century. While several technological breakthroughs are still needed, enough progress has been made to elucidate the basic mechanisms of the fusion reactions and to point fusion research to the right direction. Because of fusion and its great promise, the time when the energy of the stars will be harnessed on Earth and when the produced power will be abundant and inexpensive may not be too far in the future.

### 6.1 The Energy of the Stars

Fusion is the form of nuclear energy that is released when light nuclei combine to form heavier nuclei. The Sun and other stars are powered by fusion reactions and radiate most of the energy they produce. As with the fission reactions, the fundamental equation for the energy released is the mass-energy equivalency principle:

$$E = mc^2. \tag{6.1}$$

Scientific research on fusion started in the late 1910s. Francis Aston, a Cambridge chemist and Nobel laureate of 1922, developed the mass

**Table 6.1** Atomic masses of commonly met isotopes in fusion reactions

Isotope	Mass, u	Isotope	Mass, u
${}_1\text{H}^1$	1.007825	${}_2\text{He}^4$	4.00260
${}_1\text{H}^2$ (D)	2.01410	${}_2\text{He}^5$	5.0123
${}_1\text{H}^3$ (T)	3.01605	${}_3\text{Li}^6$	6.01513
${}_2\text{He}^3$	3.01603	${}_3\text{Li}^7$	7.01601

spectrograph that enabled precise measurements on the mass of the various elements and the discovery of isotopes. His meticulous and accurate measurements on the mass of light isotopes showed that the mass of four hydrogen nuclei is greater than the mass of one nucleus of helium. As a consequence, if the four hydrogen nuclei were to combine and form helium, there would be a “mass defect” and, hence, a large amount of energy would be released during the reaction for the formation of helium. This was caught by a British Astronomer, Arthur Eddington, who in 1920, shortly after the publication of Aston’s results announced that “...we need not look further for the source of a star’s energy.”

Table 6.1 (data from [1]) shows accurate measurements of the mass, in atomic mass units, u, of the most important isotopes in fusion reactions ( $1 \text{ u} = 1.6604 \times 10^{-27} \text{ kg}$ ).

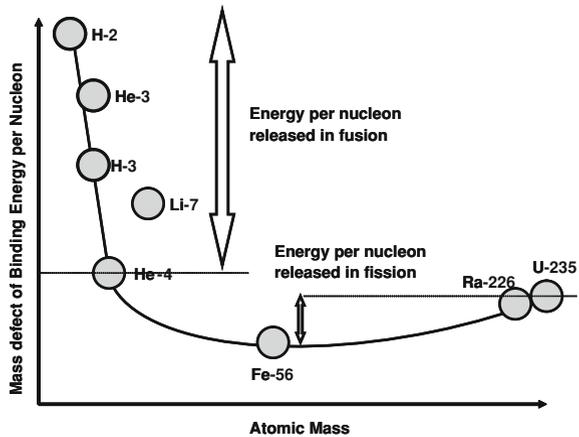
It is apparent from this table that the mass defect of the helium formation reaction,



is 0.0287 u and, since 1 u produces 931 MeV of energy, the production of a single nucleus of helium-4 from light hydrogen releases 26.72 MeV of thermal energy. When 1 kmol of helium-4 is produced (4.0026 kg) the energy released would be  $257.5 \times 10^{13} \text{ J}$ . This is a very high amount of energy. The energy produced by the formation of 41,000 kmols of helium-4 would be sufficient to satisfy the entire energy demand in the USA for an entire year. A few tons of helium-4 produced per second provides sufficient energy to power a star.

The technique of mass spectrometry was further developed in the first part of the twentieth century: more accurate instruments were developed and the mass of light isotopes was measured with a higher degree of accuracy. It became apparent that many isotopes were significantly lighter than the simple sum of their proton and neutron constituents. As a consequence, when protons and neutrons combine to form heavier nuclei, they become lighter than if they existed as independent particles. This gave rise to the concept of “mass defect per nucleon” for the formation of heavier nuclei, or equivalently to the “binding energy per nucleon.” In the example of the formation of helium-4, the mass defect per nucleon is 0.007175 u ( $= 0.0287/4$ ) and the binding energy per nucleon is the equivalent energy of 6.68 MeV. One may plot the binding energy per nucleon vs. the atomic mass of the heavier nuclei to obtain the graph depicted in Fig. 6.1. This figure shows qualitatively the binding energy of several light nuclei such as deuterium

**Fig. 6.1** Binding energy per nucleon versus atomic mass



and tritium ( ${}^2_1\text{H}$  and  ${}^3_1\text{H}$  respectively) lithium-7, helium-3 and helium-4 as well as heavy nuclei, such as uranium-235 and radium-226. The curve has an apparent minimum, which corresponds to the mid-level atomic masses in the range 50–60 u. Common metal isotopes such as iron-56 and nickel-56 correspond to these mass numbers. When reactions proceed from the left to the right of the binding energy curve and atoms combine to form heavier nuclei, fusion occurs. When reactions occur from the right to the left of the curve and atoms split, then we have fission. It is apparent from Fig. 6.1 that the amount of energy released per nucleon in the fusion reactions is by far higher than the amount released per nucleon in the fission reactions. Therefore, fusion reactors have the capability to produce significantly more energy than fission reactors per unit mass of their fuel.

Fusion reactions and Fig. 6.1 may also be used to explain the formation of the Universe and the life of the stars: Shortly after the Big Bang, the first protons and neutrons were formed as well as helium atoms from the fusion of the smaller nucleons. A few minutes after the Big Bang, the primordial matter was formed, composed of 75% hydrogen and 25% helium. Stars were formed from the gravitational attraction of these elements and their radiative energy and high temperatures are a consequence of fusion reactions, such as the one shown in Eq. (6.2). Astrophysicists have proven that stars like our own Sun will cease to radiate when their hydrogen is depleted. This type of stars will contract and become *white dwarves*. More massive stars, where the gravitational attraction is significantly higher than that of our Sun, will continue to shine with reactions that combine helium atoms to form more massive isotopes, such as those of carbon and oxygen. When helium is depleted, the light isotopes will fuse to form heavier elements. The chain of fusion reactions will continue until isotopes are formed at the region of minimum energy of the curve of Fig. 6.1. Further fusion reactions would not release energy to keep the star's material apart and the gravitational attraction will cause the star to first contract to much higher density and then to explode with a tremendous energy release. The star will then be known as a *supernova*.

**Table 6.2** Fusion reactions, temperature and density in the six stages of the life of a massive star

Stage	Principal reactions	Temperature <sup>o</sup> C	Density kg/m <sup>3</sup>
I	${}_1\text{H}^1$ or ${}_1\text{H}^2 \rightarrow {}_2\text{He}^4$	$1*10^7$	10
II	${}_2\text{He}^4 \rightarrow {}_6\text{C}^{12}$ or ${}_8\text{O}^{16}$	$2*10^8$	$1*10^6$
III	${}_6\text{C}^{12} \rightarrow {}_{10}\text{Ne}^{20}$ or ${}_{12}\text{Mg}^{24}$	$5*10^8$	$6*10^6$
IV	${}_{10}\text{Ne}^{20} \rightarrow {}_8\text{O}^{16}$ and ${}_{12}\text{O}^{24}$	$8*10^8$	$3*10^7$
V	${}_8\text{O}^{16} \rightarrow {}_{14}\text{Si}^{28}$	$3*10^9$	$2*10^9$
VI	${}_{14}\text{Si}^{28} \rightarrow {}_{26}\text{Fe}^{56}$ or ${}_{28}\text{Ni}^{56}$	$8*10^9$	$4*10^{12}$

Astrophysicists distinguish six distinct stages of a massive star before it explodes. The stages in the life of a star are chosen according to the type of fusion reactions that occur and the nuclei present. Table 6.2 shows these six stages as well as the most common fusion reactions taking place during each stage. The reactions feed the star's radiation activity. The temperature and density conditions that sustain the fusion reactions in the stars are also shown in Table 6.2 [2]. One may immediately observe that the fusion reactions take place at extremely high temperatures, where matter is in the state of plasma.<sup>1</sup> Also, that the reactions of stages II through VI take place at tremendously high densities that have never been naturally observed on Earth.

## 6.2 Man-Made Fusion

The very first, large scale demonstration of artificial fusion was the development and detonation of the hydrogen bomb (H-bomb). Fusion in the H-bomb occurs by the combination of two atoms of deuterium ( ${}_1\text{H}^2$  or simply D) to form a single atom of  ${}_2\text{He}^4$ . The fusion reaction is crudely accomplished by the detonation of a conventional nuclear weapon (the U-bomb). The blast and shock waves produced by the detonation of the U-bomb create the extremely high temperatures and pressures that are necessary for the fusion to occur. The destruction caused by the H-bomb is due to both the fusion reactions that take place as well as the action of the conventional nuclear weapon.

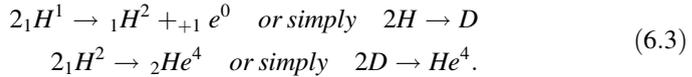
The uncontrolled and destructive explosion of the H-bomb may hardly be used for the production of heat and electricity in a safe and orderly manner. Even though humans were able to reproduce the reactions and unleash the energy of the stars, they fell short of using this energy for their own needs. Sustained and controlled fusion is needed for all peaceful uses of nuclear fusion and this has been the objective of research in several laboratories worldwide since the 1920s.

<sup>1</sup> Plasma is considered the fourth state of matter, in addition to solid, liquid and gas. In the state of plasma the electrons acquire high energies and break free from the nuclei. Thus, the plasma state resembles a gas composed of nuclei and free electrons.

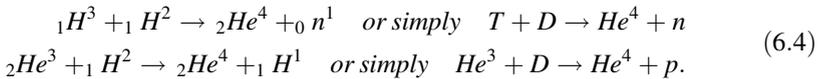
### 6.2.1 The Paths to Form Helium-4

The reaction depicted in Eq. (6.2) does not occur instantaneously in the stars, because the simultaneous collision of four hydrogen nuclei has extremely low probability to occur. Rather, the reaction occurs in two stages, with deuterium being the intermediate isotope:

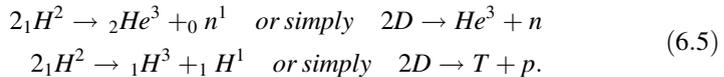
- a) The formation of deuterium by the combination of two nuclei of hydrogen.
- b) The combination of two nuclei of deuterium to form helium-4 or



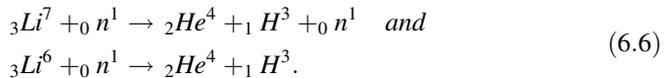
This is neither the only, nor the most probable path to the formation of helium-4. The isotopes of tritium ( ${}_1\text{H}^3$  or simply T) and helium-3 may also lead to the formation of helium-4 by reacting with a nucleus of deuterium while emitting a neutron and a proton respectively. These reactions may be written as follows:



Tritium is a radioactive, artificial isotope of hydrogen with a half-life of 12.3 years. Helium-3 is a stable but rare isotope of helium. The two isotopes may be formed by the fusion of two deuterium nuclei:



Another source of tritium is the light element lithium. Two naturally occurring isotopes of this element, with mass numbers 6 and 7, when bombarded with neutrons produce tritium and helium-4 as in the following reactions:

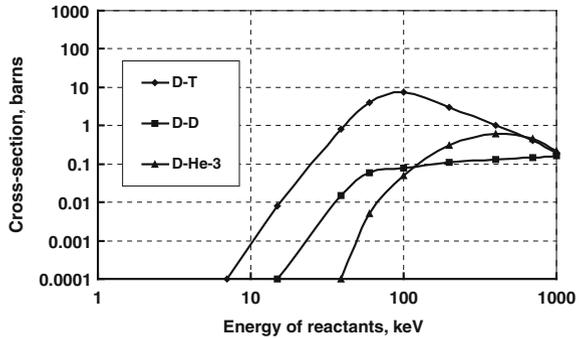


The first of the reactions in the last equation requires energy of 2.5 MeV and occurs with fast neutrons that have this level of energy, while the second reaction, releases 4.8 MeV and occurs with thermal (slow) neutrons. From the energetic point of view, the second reaction is preferable for the formation of the fuel tritium, because additional energy is produced, which may sustain the reactions.

In summary, there are three paths for the fusion to occur and for the formation of helium-4 from the reactions of the following isotopes:

1. Two deuterium nuclei (DD).
2. One deuterium nucleus and one tritium nucleus (DT).
3. One deuterium nucleus and one helium-3 nucleus (DHe<sup>3</sup>).

**Fig. 6.2** Cross-sections of three fusion reactions:  
1 barn =  $10^{-28}$  m<sup>2</sup>



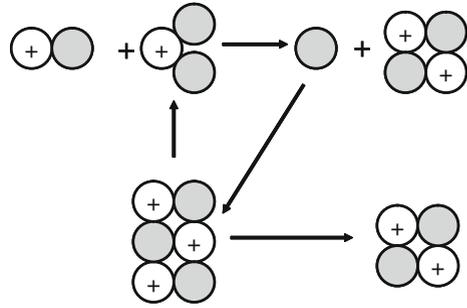
As with the fission reactions, the probability that a fusion reaction will occur is determined by the cross-section of the reacting isotopes. Figure 6.2 depicts the pertinent cross-sections for the three reactions as a function of the energy of the reactants. The data in the figure were reproduced from McCracken and Stott [2]. It is apparent in this figure that for the reactions to occur, the reactant isotopes must have very high energies, which correspond to extremely high temperatures (10 keV of energy corresponds to approximately 100 million degrees K). Also, that the DT reaction has an advantage over the two other reactions because its cross-section is significantly higher than the other cross-sections at the lower range of fuel energies. Because of these practical considerations, the DT reaction has been pursued by more laboratories internationally for the achievement of controlled fusion than the alternative reactions.

### 6.2.2 The Deuterium–Tritium (DT) Fusion Reaction

The development of fusion reactors and the harnessing of controlled fusion power is an awe-inspiring and very expensive task, which is still in the research area with many nations participating, either separately or jointly, for its accomplishment. The principal reason for its pursuit is that fusion may provide mankind with an inexhaustible energy source. Unlike other energy sources that may be exhausted in the near or far future, if appropriately harnessed, fusion will provide mankind with energy for millions of years for the following reasons:

At first, deuterium is a naturally occurring isotope of hydrogen and comprises 0.015% of hydrogen atoms. With all the water on the earth's surface the total amount of deuterium is estimated to be  $1.3 \times 10^{18}$  kg. If this quantity were used in fusion reactions, the entire population of the Earth will have enough electricity for 1.3 trillion years. It is the sheer magnitude of such numbers that makes fusion energy research a worthwhile endeavor for the human society. Secondly,

**Fig. 6.3** Nuclear fusion reactions that lead to DT fusion. Nucleons with the symbol + denote protons and shaded nucleons denote neutrons



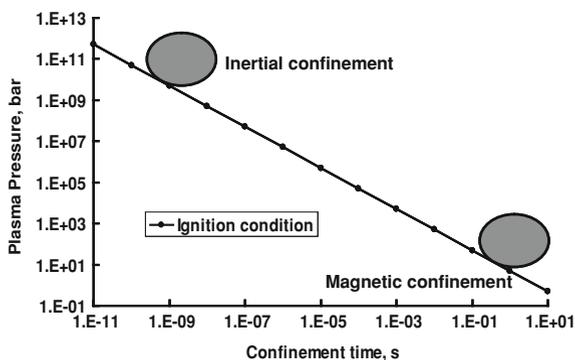
deuterium may always be produced from common hydrogen, which is one of the most common isotopes on earth. Thirdly, even if deuterium is not used for the production of tritium, there is sufficient metal lithium on the surface of the earth to supply with enough Li-6 or Li-7 for the production of tritium. Natural lithium is abundant on the crust of the earth and contains 92.6% of Li-7 and 6.4% of Li-6. The abundance of both deuterium and lithium on the earth make the proposition of producing power via the DT reaction very attractive. If the controlled DT reaction becomes a reality, mankind's energy problem will be solved.

A schematic diagram of the basic reactions that would lead to the DT fusion is shown in Fig. 6.3. Lithium-6 and deuterium are used as the fuel. Tritium is produced from the neutrons released during the DT reaction and two nuclei of helium-4 are produced as the final product. If lithium-7 were used as the fuel, an additional neutron would have been produced in the final product.

A glance at Fig. 6.2 and the values of the cross-sections of the DT reaction proves that the reaction has an optimum and significant probability to occur at the extremely high temperatures of a few hundred million degrees Kelvin, where plasma is the only state of matter. This brings the first and rather formidable challenge facing the scientists and engineers who endeavor to construct a fusion reactor: To maintain the reactor fuel at these extremely high temperatures for the reaction to occur, when it is known that any common material container would evaporate at temperatures below 3,000 K. Obviously, the fuel for the fusion reactors cannot be conventionally contained in a material container, because any contact of the fuel would vaporize the container. Scientists and engineers have agreed that the confinement of plasma in a vacuum by a strong magnetic field and the confinement of a rapidly compressed gas by its own inertia are the best methods to contain the plasma for a sufficiently long time for the fusion to occur. These two methods will be briefly described in the next section.

The second challenge scientists and engineers are faced with is that the fuel must be kept in the state of plasma for a short but significant amount of time, so that the fusion reaction will have the time to take place. This is called the *ignition condition*. A simple formula describes the ignition condition in the range of temperatures  $1.0 \cdot 10^8 \text{ K} < T < 2.0 \cdot 10^8 \text{ K}$ , which is the optimum range for the DT fusion to occur [2]:

**Fig. 6.4** The ignition condition in the confinement time-pressure diagram



$$nT\tau_c > 3 * 10^{21} \text{ keV} * \text{s}/\text{m}^3, \quad (6.7)$$

where  $n$  is the density of all the particles in the plasma, and is measured in particles per cubic meter;  $T$  is the temperature of the plasma, measured in energy units of keV ( $1 \text{ keV} \approx 10^7 \text{ K}$ ); and  $\tau_c$  is the confinement time that is necessary for the reaction to proceed. When one treats the plasma as a gas composed of nuclei and electrons, the product  $nT$  is proportional to the pressure of the plasma,  $P$ . Hence, Eq. (6.7) may be re-written in terms of the plasma pressure as follows:

$$P\tau_c > 5 \text{ bar} * \text{s}. \quad (6.8)$$

The last equation is valid under the condition that the temperature is in the range  $1.0 * 10^8 \text{ K} < T < 2.0 * 10^8 \text{ K}$ . Figure 6.4 shows this trade-off between pressure and confinement time for the ignition condition. The conditions achieved by the two confinement methods, magnetic and inertia confinement are at the two opposite ends of the line that defines the ignition condition. The two regions for magnetic and inertia confinement ignition are shown by the shaded ovals. It is apparent from this figure that, under the conditions prevailing during the magnetic confinement, the plasma must be kept at the confinement conditions for approximately 1 s. During inertial confinement, when pressures on the order of  $10^{10}$  bars must be produced, the plasma needs to be confined for only  $10^{-10}$  s. It must be noted that, in both types of confinement the plasma temperature must be between 100 and 200 million Kelvin. The confinement of any material at this temperature presents a formidable technical problem.

The third challenge fusion scientists and engineers must overcome stems from the relatively low cross-section of the DT reaction, which implies low probability of fusion. A comparison of the fusion cross-sections in Fig. 6.2 and those of the fission reactions in Fig. 4.5a, b shows that the cross-sections of the DT reaction are several orders of magnitude lower. Despite the fact that the cross-sections of the DT reaction are the most favorable of the three possible fusion reactions, the significantly lower cross-sections imply that the probability of fusion is much lower than a comparable fission reaction, even when the DT mixture is at the most

favorable conditions of plasma. At the ignition condition, the probability of fusion is only on the order of  $10^{-8}$ .

It takes a great deal of energy to produce the high temperature and pressure conditions of plasma. For sustainable fusion reactions, this energy must be recouped from the energy released during the DT reactions. If fusion is to be used routinely as an energy source, a given mass of fuel must provide several times the energy used to bring it to the state of plasma. During sustainable fusion reactions, the plasma particles should not be allowed to “cool off” significantly between fusions and must be maintained at their high energies.

### 6.2.3 Magnetic and Inertial Confinement of Plasma

The enormous mass of a star exerts a sufficient gravitational force to keep the hydrogen and helium atoms confined to a region around the star’s center, to reach the state of plasma, and to achieve ignition conditions. In the case of man-made fusion reactions, plasma must be created from the common states of the known gases and must be kept confined for sufficient time for the fusion reactions to occur. The two most commonly used methods for the confinement of plasma are:

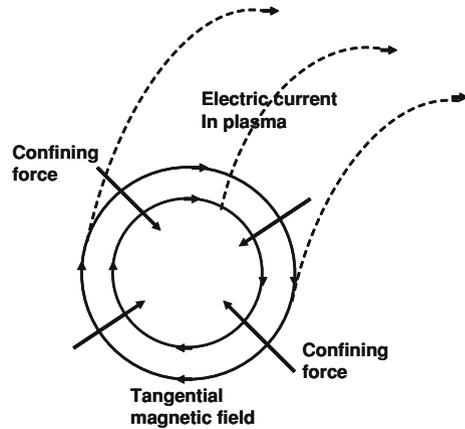
#### A. Magnetic Confinement

The magnetic confinement of plasma is based on the *pinch effect* of electric conductivity: basically, a high electric current density squeezes the material that conducts it. Since plasma is composed of a vast number of free electrons and positively charged nuclei, it conducts electricity very well.<sup>2</sup> Actually, the conductivity of deuterium plasma is approximately 10 times more than that of copper at ambient conditions, which makes plasma an excellent conductor. In addition to the *pinch effect*, the electric current creates a magnetic field around the conductor. These magnetic forces are tangential to the surface of the conductor. Therefore, electrically charged plasma creates a tangential magnetic field as well as a centripetal force that keeps it confined. However, if the plasma flows in a straight line, it would escape at the exit of the linear conductor and a constant supply of plasma would be needed with all the thermal energy expense to create the fresh plasma supply. A simple solution to this problem is to create a closed circuit for the flow of plasma by bending the conductor to form a closed, circular path and, thus, to induce the plasma to flow in a toroidal, or donut-shaped, path. The toroidal path does not have an exit. Highly energetic plasma circulates continuously in the torus and is not lost. Figure 6.5 shows schematically the circular motion of the plasma, the magnetic field induced and the centripetal confining force, which is created and keeps the plasma confined in the torus. It is apparent that plasma may circulate *ad*

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<sup>2</sup> The conductivity of plasma is oftentimes referred to as the *Spitzer conductivity*, in honor of the late Professor Lyman Spitzer of Princeton.

**Fig. 6.5** Induced magnetic field and confinement “pinch” force in the toroidal motion of plasma



*infinitum* in this toroidal path as long as the driving electric and magnetic fields are maintained.

A complication in this picture of smooth toroidal plasma flow is that the charged plasma particles in the presence of the induced magnetic field do not simply move in a closed circular path. The induced magnetic force makes the charged particles to follow solenoidal paths. The radii of the paths are called the *Larmor radii* and are given by the expression [2]:

$$r_L = 0.00457 \frac{\sqrt{AT}}{BZ}, \quad (6.9)$$

where  $A$  is the mass number of the particle,  $Z$  the charge number of the particle,  $T$  is the temperature in keV and  $B$  the strength of the magnetic field in Tesla. In the case of an electron, the Larmor radius is:

$$r_{Le} = 0.000107 \frac{\sqrt{T}}{B}. \quad (6.10)$$

The mass of a deuterium nucleus is approximately 2 u and the mass of an electron is approximately 0.00055 u. Hence, deuterium moves in a solenoidal path whose radius is 60 times greater than that of the electron.

A more serious problem with the confined toroidal motion of plasma is the flow instabilities that are associated with the motion of the plasma. These instabilities are of two kinds:

- (a) “Kink” instabilities, which cause the buckling of the torus, and
- (b) “Sausage” instabilities that constrict parts of the torus and swell other parts.

Both types of instabilities are undesirable, because they bring the plasma in close proximity or in contact with the confining walls and thus, may destroy the walls that are designed to contain the plasma. The two types of instabilities are suppressed by inducing another current to flow on the toroidal walls that contain

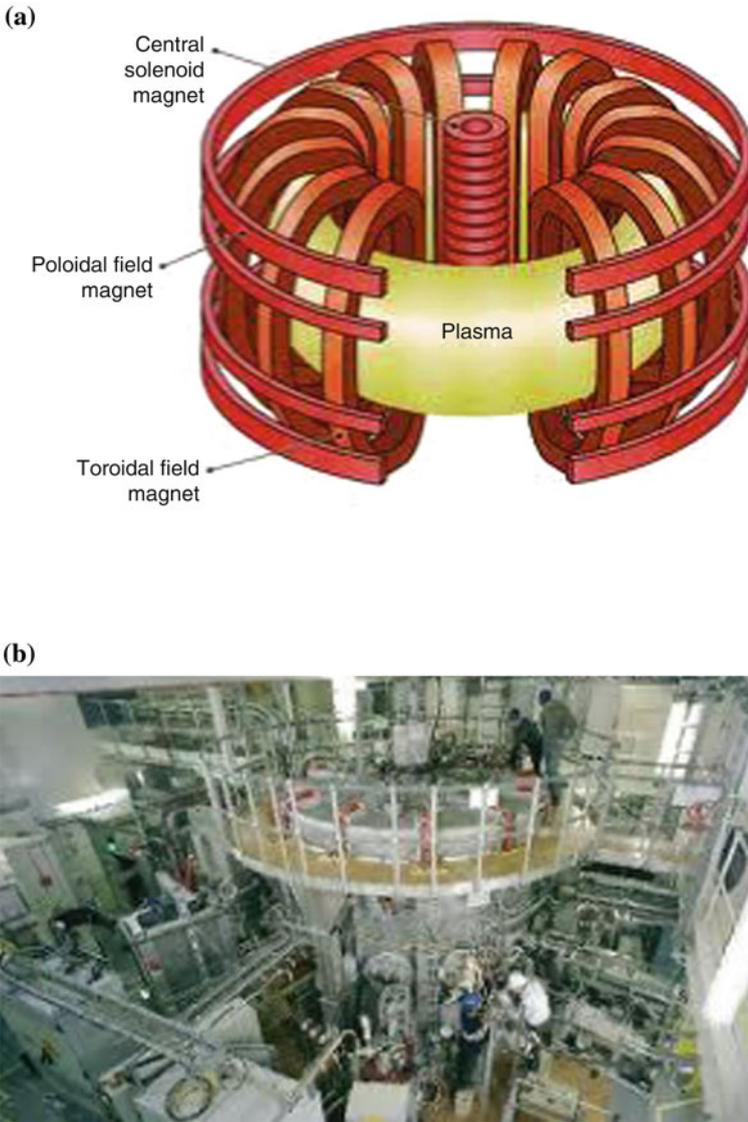
the plasma. This solenoidal current induces a stabilizing magnetic field, which suppresses both instabilities and allows the plasma to flow in a smooth torus. The toroidal *Tokamak*, reactor, invented in the former USSR in the 1960s and by now replicated in several different versions by other countries and international laboratories, is the best device that suppresses the kink and sausage instabilities and keeps the plasma well confined in a symmetrical torus. Experimental Tokamak reactors have been built in several countries for the study of nuclear fusion, including one in Princeton, NJ, which operated successfully between 1982 and 1997. A schematic diagram of the arrangement of the essential equipment and the formation of the toroidal plasma field in a Tokamak reactor is shown in Fig. 6.6a (image courtesy of the Lawrence Livermore National Laboratory). An actual photograph of the United Kingdom Tokamak reactor, which currently operates near Oxford is shown in Fig. 6.6b (image courtesy of the UK Atomic Energy Authority). The last photograph also shows the scale and complexity expected in a fusion reactor, even of experimental size.

### B. Inertial Confinement

Inertial confinement fusion (ICF) of plasma follows the method used in the hydrogen-bomb: when the deuterium–tritium mixture is compressed and heated quickly, it becomes plasma and reaches fusion conditions before the rising temperature allows it to expand and escape. The inertia of the compression process keeps the plasma confined. In this case, safety dictates that the mass of the compressed fusion fuel is by far smaller than the mass used in a hydrogen bomb. The mass of fuel is also constrained by the amount of energy needed to heat the fuel in a sufficiently rapid way, in order to reach fusion conditions. Because of the tremendous amount of energy released by fusion, burning only five milligrams of a deuterium–tritium mixture would produce energy of the order of  $10^8$  J. This is equivalent to the energy released from three gallons of gasoline. According to the ignition condition of Fig. 6.4, the DT fusion would occur when the DT mixture reaches a temperature on the order of 200 million K and pressure in excess of  $10^{10}$  bar during only a few billionths of a second.

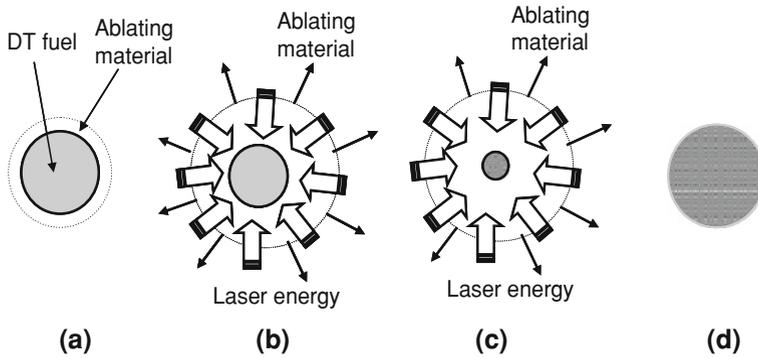
While the magnetic confinement aims at establishing a steady-state for the plasma in its toroidal motion, when fusion will occur, inertial confinement is a periodic, pulsed process. During ICF the fusion occurs when the fuel reaches favorable conditions and starts to “burn.” At this point the temperature is further increased and the fuel starts to expand. Normally, following the laws of gases, the fuel’s temperature and pressure would drop significantly during the expansion process. However, the continuous burning of the fuel releases a significant amount of energy and may sustain the high temperature and pressure during the expansion, thus sustaining the fusion process, which spreads to the entire mass of the fuel. It is this released energy that prevents the mass of the stars from collapsing because of gravitational attraction.

A commonly used method for heating and compressing the DT fuel is by *laser ablation*, which is shown in Fig. 6.7. The DT fuel is supplied in solid form as a spherical capsule, with a layer of an ablating material on its surface (a). An intense



**Fig. 6.6** **a** A schematic diagram of the Tokamak fusion reactor (courtesy of LLNL)  
**b** A photograph of the MAST Tokamak reactor at Oxford, UK (courtesy of UKAEA)

laser beam evaporates rapidly (ablates) the material. As the rapidly produced vapor leaves the surface of the fuel in a radial direction, momentum conservation causes a rapid rise of the pressure on the surface of the capsule, which starts to compress (b). If the surface of the fuel capsule is heated uniformly from all sides, the uniform and rapid increase of the pressure causes a fast increase of the density and temperature of



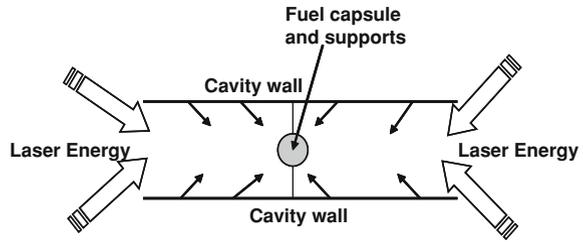
**Fig. 6.7** The four stages of the laser ablation process. **a** Fuel capsule and ablating material, **b** Laser heating and compression, **c** Onset of fusion, **d** Fusion sustained expansion

the fuel material. The fuel attains the state of plasma, reaches the ignition condition and the fusion reaction commences (c). The fusion process generates a great deal more energy, which sustains the conditions for the fusion reaction. When the ablation stops, the inertial effects cease and the capsule starts expanding (d).

Neodymium lasers that produce intense bursts of light are used for the laser ablation process. The capsules are typically made of glass or plastic material, which encloses a few milligrams of the DT fuel. Recently, multiple layers of encapsulating materials have been proposed to make the ablation/compression process more powerful. The laser ablation process may create pressures on the order of  $10^8$  bar. If applied to a capsule of 1 mm diameter of DT solid fuel with an initial density  $300 \text{ kg/m}^3$ , the rise in pressure will cause a density increase by a factor of 1,000. Under these conditions the fuel will reach a density of  $300,000 \text{ kg/m}^3$ , which is sufficient to start the fusion process in the fuel mixture [2].

A key detail in the laser ablation process is that the heating of the ablating material must be uniform. Non-uniform heating and ablation create an imbalance of the forces acting on the capsule. With non-uniform heating the ablation forces will become propulsion forces, the capsule will simply move away from the laser's focal point and the fusion will not occur. Even a 0.1% non-uniform heating will cause the capsule to fly away. The *hohlraum* (cavity in German) was invented to prevent heating instabilities and loss of the fuel. The *hohlraum* is a small cylindrical cavity made of gold, with the spherical fuel capsule supported at its geometric center as shown in Fig. 6.8 [2]. It is arranged for the laser light to enter symmetrically through the two sides of the cylinder. Part of the laser light is reflected on the gold surface and reaches the capsule from all directions. Another part of the laser light evaporates the golden surface and excites the atoms, which produce x-rays that also bombard the capsule from all sides. The combination of many side reflections and x-ray bombardment from all the sides causes uniform heating of the ablation surface, the capsule remains inside the cavity and fusion takes place.

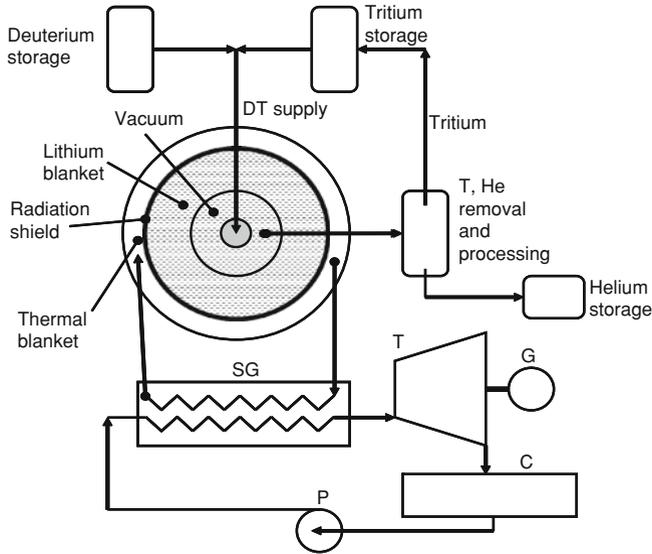
**Fig. 6.8** The *hohlraum* or “cavity” causes uniform heating of the ablation material



### 6.3 A Fusion Electric Power Plant

Controlled nuclear fusion is still in the embryonic stages of research and development. Although significant progress has been made in the understanding and the realization of the fusion process, a power plant that would solely use fusion energy for the production of electricity is still in the realm of futuristic development. Two of the main problems for the realization of a fusion power plant are the sustenance of plasma conditions at the right state for the required durations, and the harnessing of the tremendous amounts of energy released even from a very small amount of fuel. It is expected that, with the concerted and synergistic effort of several nations, technological advances will be made in the next 50–60 years, which will enable humans to successfully harness the energy of the stars. At that point, several fusion power plants will be built that will be capable to convert the thermal energy release by fusion to electricity. Although a fusion power plant is still a futuristic concept, it is not difficult to discern the main parts of this type of thermal power plant, which are depicted in Fig. 6.9:

1. The central part of the plant is the plasma reactor, which is fed with a mixture of deuterium and tritium. The reactor may be of the toroidal type (Tokomak) or may use the pulsed laser ablation method. The central part of the reactor, where fusion occurs is surrounded by a lithium-6 blanket, which absorbs the neutrons and creates tritium, with helium as a by-product. The tritium and helium products are removed and separated. Helium is stored to be used for other commercial processes. Tritium is also stored to be later combined with the deuterium and be used as the DT fuel of the reactor.
2. A radiation shield, made of lead or a similar radiation-absorbing material, surrounds the central part of the reactor.
3. A thermal blanket, which surrounds the reactor and removes the heat generated in the center of the fusion reactor. The thermal blanket is cooled by the circulating coolant, which is water, helium or a molten metal (liquid Na or K).
4. A number of steam generators (SG), essentially large heat exchangers, where the reactor coolant transfers its energy to raise steam.
5. The turbine or series of turbines (T), generators (G), condenser (C), recirculation pump (P) and cooling system (not shown in the figure), are similar to the equipment used in the conventional thermal power plants. In this part of the



**Fig. 6.9** A schematic diagram of a conceptual design of a fusion power plant

plant, steam expands, and electricity is generated. Subsequently, steam is condensed and follows the path of a closed cycle that feeds it back to the steam generator as liquid water.

Perhaps the most important difference of the conceptual design of the fusion power plant to the design of the other thermal power plants is that the fusion plant must produce tritium, which is one of the essential elements of its fuel. Because of this, the fusion reactor is also a breeder reactor. Unlike the fission breeder reactors where the produced plutonium stays and is used in the encapsulated reactor, in the fusion power plants tritium is produced with another gaseous product, helium. Because the two form a homogeneous gaseous mixture, it will be necessary to continuously treat the fuel and remove the helium product. The only practical and available technique at present to accomplish this separation process involves centrifuging the gaseous mixture, a process that consumes high amounts of energy.

The exact design of the fusion power plant will greatly depend on the method used to achieve fusion. If the magnetic confinement method is chosen, the plasma torus that will be used will have to combine most of the parts that are included inside the radiation shield of Fig. 6.9, with an inlet for the fuel and outlets for the helium product. If the inertial confinement method is chosen, the lasers that would provide the ablation power for the fuel pellets will have to be incorporated in the design of the power plant. However, fusion research still needs to overcome several technological barriers before a fusion power plant is to be developed for the immediate future and, for this reason, at present there are no immediate plans to build a fusion power plant. It is almost certain that a future fusion power plant

will have the basic components 1–5 as listed above. However, as it often happens with futuristic concepts, when fusion plants become a reality, their actual design and processes will somehow diverge from the conceptual designs that have been promulgated in the scientific literature.

## 6.4 Environmental Considerations

Fusion energy produces significantly less and at a lower level nuclear waste than fission energy: The main product of the fission reactions is  ${}^4_2\text{He}$ , which is not radioactive. Also, the fuels for the fission reactions, deuterium and lithium are not radioactive either, and are abundant and well-distributed on the surface of the earth. Unlike the fission reactions, there are no radioactive daughter isotopes that are produced in large quantities. The only clearly radioactive isotope, tritium, is subsequently used as a fuel and, in addition, has a relatively short half-life of 12.3 years. This implies that there is virtually a very small amount of waste that will come from the fuel cycle and the fusion products and, this waste will decay in a relatively short amount of time.

Another significant difference between fission and fusion power plants is that the fuel will be continuously supplied and in very small quantities to the reactor. Fission reactors are charged once every  $1\frac{1}{2}$ –2 years and all the fuel to be used during this time is enclosed in the fission reactor. In contrast, fusion reactors may be continuously supplied with small amounts of fuel. Safety systems may be easily implemented in the fusion reactors to interrupt the supply of fuel and to immediately stop the fusion reaction, if there is any perceived threat to the environment. It is apparent that a fusion power plant and the surrounding region will not be subjected to the dangers of a loss of coolant accident or a meltdown.

The fusion reactor itself and the material of the reactor will become contaminated and will contribute to nuclear waste. As shown in Fig. 6.9 a fusion power plant will comprise several systems that may become contaminated. At first, the radiation shield will be subjected to a high neutron flux that will contribute to its contamination. Secondly, some of the neutrons will inevitably pass to the thermal blanket and the circulating coolant. This will lead to the contamination of the heat exchanger material and, possibly, to the contamination of the steam, which will carry the contaminants to the turbine and the condenser. Contamination of the turbine-condenser system may be avoided to a large extent by including an intermediate coolant circuit as in the case of the Breeder Reactor power plants that are shown in Fig. 5.13. Even though the nuclear waste from a fusion power plant is significantly less than the waste from a fission plant, fusion energy is not environmentally benign and, before we embark on large-scale applications of this type of energy we must, first, solve the problem of plant decommissioning and disposal of the produced nuclear waste.

## 6.5 “Cold Fusion,” Other Myths and Scientific Ethics

As mentioned in several parts of this chapter, if successfully harnessed, fusion energy has the potential to solve the energy needs of humanity for the entire foreseeable life of our planet. Unlike other alternative energy sources that may supply only a small fraction of the energy needed, fusion, in combination with a transition to a hydrogen economy for transportation fuels, has the potential to supply the entire energy demand of the planet and, therefore, is *the answer to the energy problem of humanity*. For this reason, there are many scientists, who find irresistible the role of “inventor of fusion” and the accompanying title of “savior of humanity.” As a result of this ambition, since fusion was discovered, there have been a number of false scientific claims, which have attracted international attention, including the following:

### 6.5.1 Muon Atomic Fusion

While studying the properties of muons that are produced by cosmic rays in the upper parts of the atmosphere, Professor Frank of Bristol University, in 1947 promulgated the opinion that if the electron in the deuterium atom is substituted by a negative muon,<sup>3</sup> the orbit radius of the muon would be roughly 200 times shorter than that of the radius of the electron and, hence, the new *muon deuterium* would be 200 times smaller than the normal deuterium atom. With such diminutive atoms, the repulsive forces developed between atoms would be significantly weaker and fusion would be much easier to achieve.

Upon closer examination of this fusion concept, two facts became quickly known: first, the muon is unstable with half-life on the order of nanoseconds and, second that the energy produced in a DT reaction is significantly less than the energy required for the production of a free muon. Even if it were possible to use muon deuterium for fusion, the net energy that would be generated would be negative. However, the latter problem could be resolved if the produced muons would be re-used in several reactions. Considerable analytical and experimental research was carried on this subject, which involved scientists from Britain, the Soviet Union and the United States. The conclusion of the combined research efforts is that, although the concept of fusion with *muonic atoms* is tantalizing, its application for the production of large amounts of energy is not a possibility.

### 6.5.2 Sonoluminescence

Sonoluminescence is the light/illumination produced from sound waves. It is well known that most liquids contain extremely fine bubbles of less than one

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<sup>3</sup> A muon is an unstable subatomic particle, about 200 times heavier than the electron.

micrometer size. These tiny bubbles respond to sonic or supersonic waves, which are essentially pressure fluctuations. When the gas in a bubble is compressed, its temperature rises significantly. The reason for this rise is that, because of the very small area of the bubble and the short duration of the compression, heat does not escape from the tiny bubble. The compression process takes place almost isentropically according to the well-known expression for isentropic processes:

$$\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}, \quad (6.11)$$

where  $\gamma$  is the ratio of the specific heats of the gas in the bubble. Since the pressure ratio in sonic and supersonic waves is very high, the temperatures produced in the tiny bubbles may be very high too. For several years it was speculated that the high temperatures produced in a dissolved bubble may produce plasma. This hypothesis was put forward in many scientific events, including the 3rd International Conference on Multiphase Flow (ICMF-98) in Lyons, France. The discussions in all these scientific events were inconclusive, mainly because there were not any direct observations of neutrons or any other radioactive materials, which are the signatures of all fusion reactions. However, speculation on the attainment of fusion reactions by sonoluminescence was rampant in the 1990s and several large-scale experiments were undertaken to demonstrate the claims.

Reporting on one of these experiments in 2002, Rusi Taleyarkhan of Oak Ridge National Laboratory (ORNL) and several of his colleagues claimed to have observed both the neutron production of the right energy (2.45 MeV) as well as the tritium in their sonoluminescence experiments. They used acetone made of deuterium instead of normal hydrogen atoms ( $C_3D_6O$ ). This team claimed that neutrons were not observed when they substituted normal acetone,  $C_3H_6O$ , in their experimental facility. Because of the enormous implications of the claim, the director of ONRL took the correct scientific stand and asked two independent teams to verify the claim. Both of these teams did not find any evidence of neutrons or tritium in the reproduced experiments with  $C_3D_6O$  and concluded that the originally observed neutrons from  $C_3D_6O$  were due to an experimental error. Later, a team at the University of Illinois showed analytically that several endothermic chemical reactions, which take place during the sonic compression, consume a significant amount of thermal energy and make it impossible for plasma to be formed and fusion to occur with  $C_3D_6O$ .

### ***6.5.3 Cold Fusion in a Test-Tube***

Perhaps the most notorious scientific scandal was perpetrated with the claim of “cold fusion in a test-tube” by two researchers of the University of Utah: Stanley Pons and Martin Fleishman held a press conference during March of 1989 and announced to the world they have achieved fusion in an electrolysis cell, kept at

room temperature and that the University was filing for patents for this process. During electrolysis an electric current separates water into its constituents, oxygen and hydrogen, which are collected at opposite metal electrodes. Pons and Fleishman used heavy water,  $D_2O$ , and palladium electrodes. It is well-known that certain metals, including steel and palladium, absorb hydrogen in their atomic structure. Essentially, Pons and Fleishman claimed that the absorption forces in the palladium metal were strong enough to compress the produced deuterium atoms to a state of plasma and to cause a fusion process. In the beginning, their claim was solely based on the temperature rise they observed in their electrolysis cell. Pons and Fleishman claimed that more energy was released than was put in the cell and attributed the difference to fusion that occurred in the electrolytic cell.

This observation was very surprising to the scientific community, because hydrogen absorption in metals is a very well known process, which has been studied by many others, without any indication of a fusion reaction. An explanation was immediately offered by Pons and Fleishman that the onset of tiny cracks in the metal would release sufficient energy for the fusion to occur.

A major complication in the whole process was that the research results were presented in a press conference and not in a scientific forum, where the normal peer review process would take place. No scientific questions were asked in this conference. The journalists, who are not scientists trained to ask the right questions, accepted the claim unquestionably and lauded the two professors as the greatest innovators of the twentieth century. The story was rapidly disseminated by the popular media, by e-mails and the internet, which at the time was in its embryonic stage. A few weeks later Pons and Fleishman submitted a paper to the leading scientific journal *Nature*, but when the scientific editor asked for details of their experiments they claimed that they did not have the time to provide the information and withdrew the paper. Instead, they gave several press conferences to the impressionable journalists that flocked to Utah and made their paper available through the internet, by e-mail in text file. At the same time, the President of the University of Utah announced in another press conference the initiation of a “Center for Cold Fusion” with funds provided by an “anonymous donor.” It was later revealed that there was not such a donor and that the funds came from within the endowment of the University, without the knowledge of the University Trustees.

Many accomplished scientists in several countries around the world had several reasons to doubt this claim: At first the experiments were conducted without any reference to control experiments with normal water,  $H_2O$ . Secondly, the peak of the gamma-ray radiation emitted by the neutrons during the experiment was shown to be 2.5 MeV, when the correct energy would have been 2.2 MeV. Pons and Fleishman never explained this discrepancy, but in a later press release the peak energy was “corrected” to 2.2 MeV. Thirdly, when measurements of the neutron flux were communicated, its values were determined to be too small for fusion to have occurred.

With such an important scientific discovery at stake, the scientific community was mobilized and many laboratories around the world attempted to reproduce the

Pons and Fleishman experiments. In the beginning, a few laboratories showed positive or inconclusive results, but soon afterwards all laboratories agreed that the experiment could not be duplicated as the authors claimed. Pons and Fleishman themselves, when challenged to reproduce their experiment, admitted that they were unable to reproduce their results and substantiate their claims. At the same time, the U.S. Energy Research Advisory Board investigated the matter, but they could not find anything that would substantiate the claim of “cold fusion.” After a great deal of investigation, a skeptical scientific community looked carefully at the multitude of new scientific data, came to the conclusion that the claim of “cold fusion,” as presented by Pons and Fleishman, was false and absurd and disseminated these conclusions to the world in no uncertain terms. The aftermath of this scientific ordeal, which lasted for almost four months, was rather sad: after several inquiries, the two scientists were asked to leave their University positions. The then President of the University of Utah, who blindly backed their claim with the investment on a “center,” was forced to resign and was soon replaced.

#### ***6.5.4 Ethical Lessons from the “Cold Fusion” Debacle***

Securing abundant food and energy are the most important conditions for the assurance of the humanity’s future. When it comes to energy, there have been several recorded claims that have proven to be mere exaggerations or even patently false. A search in the popular press or the internet will prove that, even today, there are several devices, engines and processes whose claims violate the laws of thermodynamics. Behind each one of these engines or processes is usually a greedy “scientist,” a gullible “company executive” or a misinformed and poorly educated “engineer.” The popular press adores and strives on sensational news, such as “cold fusion,” “cars running on water,” or “an engine that defies gravity.” However, the popular press and the internet are not subjected to any rigorous peer review processes. They are not scientific fora, and not everything that is reported in them is necessarily correct or true.

There is a true scientific forum that is open to all scientists, the scientific journals and conferences, which depend on the peer review process. This forum has served science and scientists for more than three centuries and reported all the significant scientific advances, inventions and failures. This scientific forum, and not the popular press, has promoted and created the Nobel laureates and it is to this forum of scientists/peers that every scientist is responsible and held accountable.

Unlike other more esoteric scientific subjects, the production of energy and its environmental effects are very important subjects to the human society and have generated a great debate. Parts of this debate have been carried by the popular press and disseminated fast by an uncontrollable internet. Oftentimes, opinions in this debate have been framed by the popular press as “scientific beliefs” of certain individuals. One must resist this framing of the scientific debate and must recall that modern science has progressed since the days of Galileo, not by a set of

“beliefs,” not by blindly sticking to a religious, political or philosophical framework of ideas, but by accurate measurements of the natural phenomena and the rational interpretation of the measured data. Good scientists take accurate and verifiable measurements, draw rational conclusions, and report them first to the scientific community through peer-reviewed publications or scientific conferences. Any deviation from this time-honored scientific method of inquiry and reporting should be met with doubt and suspicion of motive.

### Problems

1. How many hydrogen atoms are there in  $1 \text{ m}^3$  of water? Assuming that these atoms combine to form helium-4, how much thermal energy may be produced?
2. A secondary source of energy for the stars is the combination of three helium-4 nuclei to form a  $\text{C}^{12}$  nucleus. The atomic mass unit (u) is defined as 1/12th of the mass of  $\text{C}^{12}$ . How much energy is released from the combination of 100 kmols of  $\text{He}^4$  to form  $\text{C}^{12}$ ?
3. The decomposition of water to hydrogen and oxygen molecules consumes 286,000 kJ/kmol and the decomposition of molecular hydrogen to atomic hydrogen an additional 216,000 kJ/kmol. Assuming that the conversion of hydrogen atoms to deuterium and, subsequently, to helium-4 were possible, how much net energy may be produced by the hydrogen atoms in 1 kg of liquid water? What conclusions do you draw from this number?
4. Assume that the conversion of hydrogen atoms to deuterium and, subsequently, to helium-4 is made a reality in thermal power plants with 35% overall efficiency and that all the hydrogen is derived from water. How much hydrogen would be needed to supply the entire annual electric demand of the United States? How many  $\text{m}^3$  of decomposed water does this hydrogen quantity correspond to?
5. The DT reaction appears to be the best candidate for sustained fusion. If the tritium is obtained from naturally occurring lithium and the deuterium is obtained from water, how many tons of Li and  $\text{H}_2\text{O}$  will be needed annually to produce the entire electric demand for France, which in 2008 was 490 TWh? Assume that the fusion thermal power plants' overall efficiency is 32%.
6. Equation (6.6) for the production of tritium requires that lithium be irradiated with neutrons. Suggest a method for the production of neutrons and describe an engineering system to be used for the collection of the tritium produced.
7. What are the temperatures of deuterium, tritium and helium-3 at energies, 10, 30, 100, 300 and 1,000 keV?
8. Explain by using a great deal of quantitative information why the deuterium–tritium reaction is considered the best reaction for sustained fusion.
9. Plasma pressures of  $10^4$  bar may be routinely created during an isentropic compression. What is the minimum confinement time (in ms) that would be necessary for fusion reactions to occur during isentropic compression?
10. Calculate the Larmor radii of the deuterium and tritium ions at  $10^6$  K and  $B = 100$  Tesla.

11. Explain in detail what is a “hohlraum” and how fusion is facilitated by it.
12. Explain in an essay of 450–500 words the advantages and disadvantages of magnetic and inertial confinement processes for the attainment of sustained fusion. What engineering problems do you foresee?
13. What are the ethical lessons for an engineer from the several false claims on the achievement of “cold fusion?”
14. “Fusion energy may supply the energy needs of the entire human population for millennia. This fact alone justifies the huge investment required for the realization of sustained fusion.” Comment in a 250–300 word essay.

## References

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