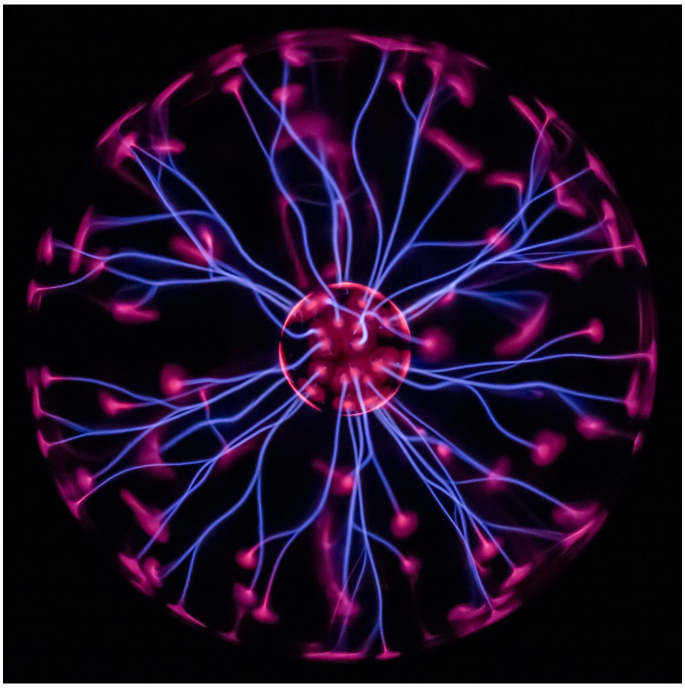
LIVING WITH PLASMAS



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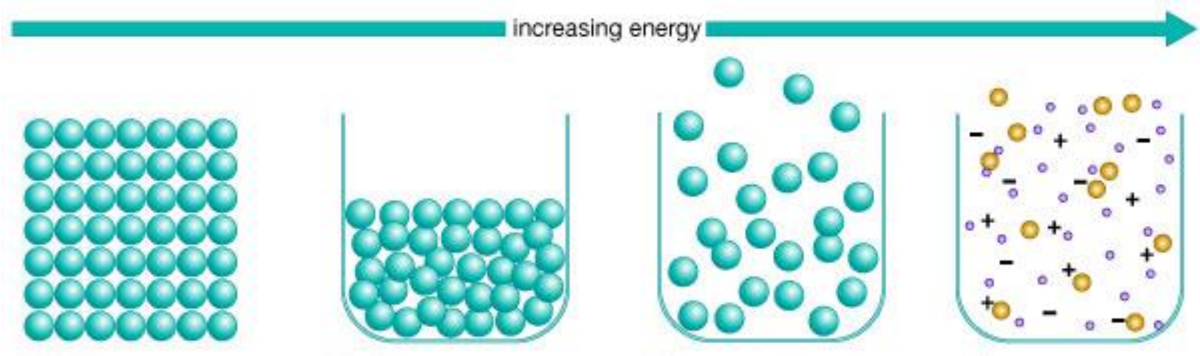
Plasma: The Fourth State, or the First State?

The States of Matter

We are familiar with three states of matter as taught in the school: solid, liquid and gas. We are also taught that adding heat leads to breaking of bonds between molecules and a substance changes from one state to the next, say from solid to liquid and from liquid to gas. For example, adding heat changes ice to water; and adding heat to water changes it to vapour, that is, gas.

What happens when we further add heat to a gas? Adding heat energy to gas breaks the internal bonds of the individual atoms, and in the process the atoms lose some electrons and get ionised, and electrons are freed. When this happens to a significant number of atoms, the resulting collection of electrically charged particles forms an ionized gas called plasma (Figure 1).



Solid: Molecules in a solid are arranged in regular repeating patterns. They are held in place firmly and can vibrate in a limited area about their mean positions.

Liquid: Molecules in a liquid flow easily around one another. However, they do not fly apart due to attractive forces between them. Liquids assume the shape of their containers.

Gas: Molecules fly in all directions in a gas at great speeds. Being very far apart from each other, attractive forces between them are insignificant.

Plasma: At the very high temperatures of stars, atoms lose their electrons. The mixture of electrons and nuclei is the plasma state of the matter.

Figure 1: The States of Matter (Picture Source: *Encyclopaedia Britannica*)

When the Universe Began

As we know today, soon after the universe began in a Big Bang (Figure 2), it was dominated by plasma at high temperature. What is more interesting is the fact that plasma continues even today to comprise more than 99 percent of our visible universe! In the beginning there was plasma and that is where we all came from! And it continues to play a major role in our universe even today, though it is not so apparent!

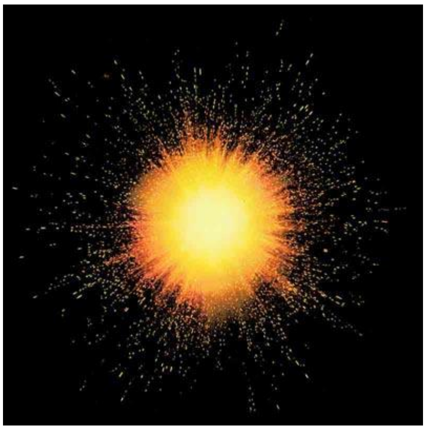


Figure 2: The Big Bang: Artist's perception
(Source: one-mind-one-energy.com/images/big-bang.jpg)

If the hot plasma dominated in the beginning of the universe, how was the matter in various states formed? Well, our universe was formed by heat removed from a hotter, more weakly bonded state. When plasma cooled, it formed a gas. On further cooling gas turned to liquid and then to solid. As matter cools, it reaches temperatures at which the atoms and molecules bind together, condensing to form the next state of matter in the cooling sequence. The predominance of plasma in the early universe continues even today. Despite the fact that material in our immediate surroundings is much cooler than the early plasma, plasma remains the most prevalent form of matter in the universe!

As stated earlier, nearly all the visible matter in the universe exists in the plasma state, occurring predominantly in this form in the Sun and stars and in interplanetary and interstellar space. Do we find plasmas on the Earth? Lightning (Figure 3A), auroras (Figure 3B), and welding arcs are plasmas; plasmas exist in neon and fluorescent tubes, in the crystal structure of metallic solids, and in many other phenomena and objects. The Earth itself is immersed in a tenuous plasma called the solar wind, and is surrounded by a dense plasma called the ionosphere.

Figure 3A
(Source: wikigag.com)

Figure 3B
(Source: images.nationalgeographic.com)

In space the dominant plasma formation process is photionisation, wherein photons from sunlight or starlight are absorbed by an existing gas, causing electrons to be emitted. Since the Sun and stars shine continuously, virtually all the matter becomes ionized in such cases, and the plasma is said to be fully ionized (Figure 4). This need not be the case, however, for a plasma may be only partially ionized. A completely ionized hydrogen plasma, consisting solely of electrons and protons (hydrogen nuclei), is the most elementary plasma.

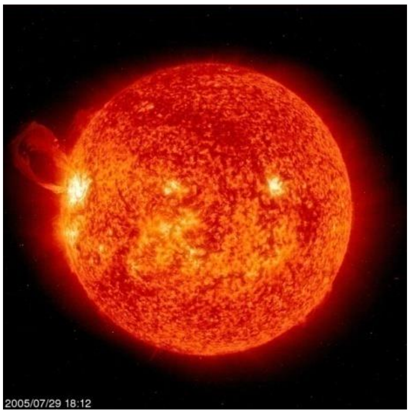


Figure 4: The Sun (and stars that shine continuously) have virtually all the matter existing in the plasma state (Source: www.universesimplified.com)

Plasma deserves respect both as an ancestor and as a major player in today's world. Clearly the usual sequence of states of matter should be reversed, with plasma not merely added to that list, but put first to lead that list, followed by gas, liquid and solid!

The Plasma State

In physics, plasma is regarded as an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles, produced when the atoms in a gas become ionized. The negative charge is usually carried by electrons, each of which has one unit of negative charge. The positive charge is carried by atoms or molecules that are missing those same electrons. It is possible that electrons missing from one type of atom or molecule (resulting in positive ions) become attached to a neutral atom or molecule (resulting in negative ions). We then have a plasma containing both positive and negative ions. The plasma state is unique due to the importance of electric and magnetic forces that act on a plasma in addition to gravity. Since the electromagnetic forces can act at large distances, plasma can act collectively like a fluid even when the particles seldom collide with one another!

Development of Plasma Science

Is it possible to produce plasma in the laboratory? The modern concept of the plasma state is of recent origin, dating back only to the early 1950s. What makes its history most fascinating is the fact that it is interwoven with many disciplines. Three basic fields made early contributions to the development of plasma physics, viz. i) study of electric discharges, 2) magneto-hydrodynamics (MHD) in which conducting fluids like liquid metals, electrolytes and plasmas are studied; and 3) kinetic theory. Let us briefly describe how our understanding of plasma physics that has evolved over the decades.

It all started with interest in the *electric-discharge phenomena* during the early 19th century. Michael Faraday (1791-1867) in the 1830s; and later in 1890s, J J Thomson (1856-1940) and John Sealy Townsend (1868-1957) laid the foundations of the present understanding of the phenomena (Figure 5). Incidentally all three of them were English. It was Irving Langmuir (1881-1957) and Lewi Tonks (1897-1971) in United States who introduced the term ‘plasma’ in 1923. They were investigating electric discharges to designate those regions of a discharge in which certain periodic variations of electrons could occur; and called them plasma oscillations. Langmuir called the medium that carried these currents "plasma" apparently because of its lifeblood-like behaviour, and the name stuck.

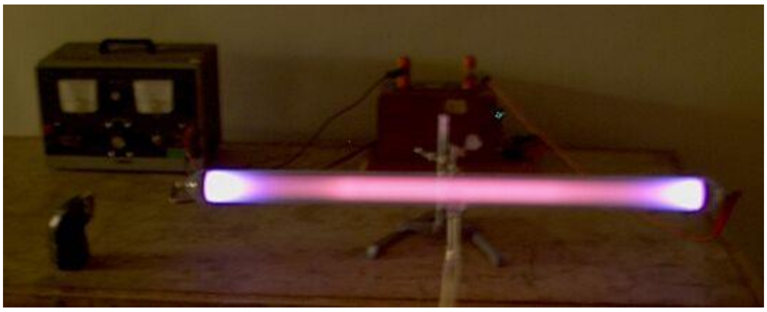


Figure 5: Discharge of electricity through gases (Source: web.physics.ucsb.edu)

The collective behaviour of charged particles in magnetic fields and the concept of a *conducting fluid* are implicit in magnetohydrodynamic (MHD) studies. It essentially implies the study of motion of charged fluids in magnetic fields. In 1930s, new solar and geophysical phenomena were being discovered, and many of the basic problems of the mutual interaction between ionized gases and magnetic fields were being studied. Studies of Hannes Alfvén (1908-1995), a Swedish physicist, on MHD along with his contributions in the studies of space plasmas, led to his receipt of the Nobel Prize for Physics in 1970. He described the class of waves in MHD now known as Alfvén waves.

The study of electric discharges and the study of the behaviour of conducting fluids in magnetic fields were unified by the introduction of the *Kinetic Theory* as applied to the plasma state. Essentially, like gas, plasma consists of particles in random motion, whose interactions can be through long-range electromagnetic forces as well as via collisions. In 1905, Hendrik Antoon Lorentz (1853-1928), a Dutch physicist, applied the kinetic equation for atoms (formulated by the Austrian physicist Ludwig Eduard Boltzmann) to the behaviour of electrons in metals. Later, various physicists and mathematicians in the 1930s and 1940s further developed the plasma kinetic theory. Ever since, the interest has mainly increasingly focused on the plasma state itself. Space explorations, development of electronic devices, importance of magnetic fields in astrophysical phenomena, and the quest for controlled thermonuclear power (nuclear fusion) reactors all have stimulated such interest.

Yet, many problems remain unsolved in space plasma physics research, owing to the complexity of the phenomena. For example, to describe the solar wind - the stream of charged particles moving radially outward from the sun, we must consider the effects of gravity, temperature, pressure, and the electromagnetic fields encountered making the calculations quite complex.

Producing and Confining Plasmas

Plasmas do not usually occur naturally on the surface of the Earth, one notable exception being the solid-state plasmas in metallic crystals. Plasmas therefore must be produced artificially for laboratory experiments and technological applications. Since the atoms of alkalis like potassium, sodium, and caesium have low ionization energies, plasmas may be produced from them by applying heat directly to them at temperatures of about 3,000 K. It is a different matter with gases though. In most of the gases, before any significant degree of ionization is achieved, temperatures in the neighbourhood of 10,000 K are required. A convenient unit for measuring temperature in the study of plasmas is the electron volt (eV). 1 eV is the energy gained by an electron in vacuum when it is accelerated across one volt of electric potential. We may note that 1 eV equals 12,000 kelvins. The temperatures required for self-ionization range from 2.5 to 8 eV. Incidentally, these are the typical values of energy needed to remove one electron from an atom or molecule.

Because all substances melt at temperatures far below that level, no container yet built can withstand an external application of the heat necessary to form a plasma. So how do we heat a gas to produce plasma? One technique is to apply an electric field to the gas to accelerate and scatter any free electrons, thereby heating the plasma "internally". Incidentally, this type of heating is called "ohmic" heating. It is similar to the method in which free electrons in the heating element of an electric oven heat the coil. Because of their relatively small energy loss in elastic collisions, electrons can be raised to much higher temperatures than other particles. For plasma formation a sufficiently high electric field needs to be applied. The exact value, however, would depend on geometry and the gas pressure. The electric field may be set up via electrodes or by transformer action, in which the electric field is induced by a changing magnetic field. Laboratory temperatures of about 100,000,000 K, or 8 kiloelectron volts (keV), with electron densities of about 10^{19} per cubic metre (which is really a very low density compared to the gas densities we come across in day-to-day life!) have been achieved by the transformer method. The temperature is eventually limited by energy losses to the outside environment.

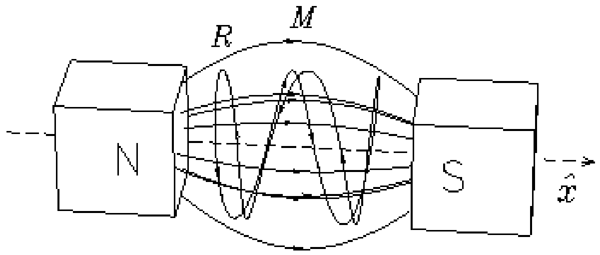


Figure 6: A magnetic mirror configuration: A simplified representation (Source: jick.net)

Extremely high temperatures, but relatively low-density plasmas, have been produced by the separate injection of ions and electrons into what is known as the "*magnetic mirror* system" (Figure 6). In this system, a charged particle is reflected from high density magnetic field to low density magnetic field as shown; and this is how the charge remains "confined" in the region of the magnetic mirror. A magnetic mirror is essentially a device using a particular arrangement of magnetic fields for confinement of a hot electrically charged plasma.

Toroidal (donut shaped) magnetic fields are also used to produce a high temperature plasma and confine it, say, in a thermonuclear fusion reactor to produce fusion energy. Indeed, energy from controlled thermonuclear fusion reactors may become a reality in coming years. Other methods have used the high temperatures that develop behind a wave that is moving much faster than sound to produce what is called a shock front. Laser beams have also been employed for the purpose.

How Plasmas are produced in Nature

We saw that a gas needs to be heated to very high temperatures to produce plasmas. We come across several phenomena in nature in which plasma heating and ionization occur in ways similar to what we described earlier while discussing production of plasma in a laboratory. In lightning-induced plasma, the electric current carried by the stroke heats the atmosphere in the same manner as in the ohmic heating technique. In solar and stellar plasmas the heating is internal and caused by nuclear fusion reactions. In the solar corona, the heating occurs because of waves that propagate from the surface into the Sun's atmosphere, heating the plasma much like shock-wave heating in laboratory plasmas.

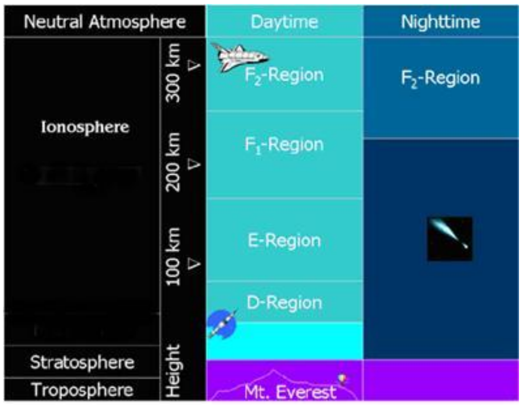


Figure 7: The ionosphere with its major regions at various heights
(Source: solar-center.stanford.edu)

In the ionosphere (Figure 7), ionization is accomplished not through heating of the plasma but rather by the flux of energetic photons from the Sun. Incidentally, ionosphere is the outer layer of the atmosphere (at a height between 200-500 km) with high concentration of electrons and ions that makes for radio wave propagation possible. Far-ultraviolet rays and X-rays from the Sun have enough energy to ionize atoms in the Earth's atmosphere. Some of the energy also goes into heating the gas with the result that the upper atmosphere, called the thermosphere is quite hot. These processes protect the Earth from energetic photons much the same way as the ozone layer protects terrestrial life-forms from lower-energy ultraviolet light. The typical temperature 300 kilometres above the Earth's surface is 1,200 K, or about 0.1 eV. Although it is quite warm compared to the surface of the Earth, this temperature is too low to create self-ionization. When the Sun sets with respect to the ionosphere, the source of ionization ceases, and the lower portion of the ionosphere reverts to its no-plasma state. Some ions, in particular singly charged oxygen (O^+), live long enough that some plasma remains until the next sunrise. In the case of an aurora, plasma is created in the night time or daytime atmosphere when beams of electrons are accelerated to hundreds or thousands of electron volts and smash into the atmosphere.

Plasmas in Everyday Life

Almost all electrical devices rely on electronic chips. Not just our computers, but our cars, our microwave ovens, our alarm clocks - all these gadgets have chips inside. And none of these chips could be manufactured without using plasma. That is because plasma technology is capable of forming transistors and wires that are much smaller than the width of a single hair. Without plasma, the transistors would have to be made much bigger, making the chips more expensive, slower, and much less powerful.

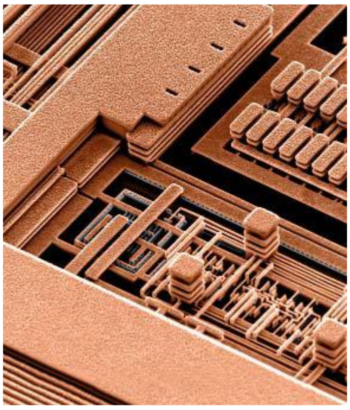


Figure 8: In this microscope photo of the wiring on a chip the smallest wires are more than 100 times thinner than a single hair
(Source: Computer Chips and Plasma, www.plasmacoalition.org)

Cars, bridges, ships, jet engines, pipelines, hot-water systems, the metal framework of buildings, - in fact most manufactured goods depend on thousands of metal-to-metal joints. Many of those joints are welded using plasmas.

Both day and night, most of the light we work by is due to fluorescent lamps, say, either tube lights or CFLs. In all these sources is produced by plasma. Plasma displays have become a part of our lives (Figure 9A and Figure 9B). We see plasma displays on store signs and in ads promoting large-screen, flat-panel plasma television sets. The flat plasma display is a major flat panel display technology today in High Definition TV market.

Figure 9A: Panasonic's 145 inch plasma TV
(Source: Panasonic Corporation)

Figure 9B: Plasma Signage
(Source: news.slacs.stanford.edu)

In the last decade, research on the use of low temperature plasmas in medicine has intensified, and today plasmas are poised to dramatically affect healthcare. Scientists have discovered ways how plasmas can be applied directly to living tissues to deactivate pathogens; to stop bleeding without damaging healthy tissue; to disinfect wounds and accelerate wound healing; and to selectively kill some types of cancer cells.

Scientists have developed several novel ways of producing plasmas that are suitable for sterilization and decontamination. These plasmas are "cold" in the sense that the temperature of the plasma forming gas remains close to room temperature. Consequently the plasma does not damage the surfaces it comes in contact with.

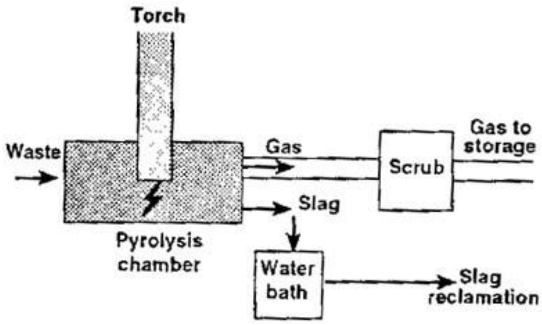


Figure 10: A Plasma Pyrolysis Plant (schematic)
(Source: cO3.apogee.net)

In plasmas the temperature of the charged and neutral particles can become much higher than is possible with incineration, so they can destroy waste more thoroughly. Furthermore, creating high temperature thermal plasma requires little gas flow because no air or oxygen is required, while an incinerator requires large amounts of air to burn wastes. Consequently plasma furnaces (pyrolysis chambers) could be used instead of incinerators to process municipal or medical waste more thoroughly and with less combustion exhaust (Figure 10). In the figure, the "torch" is a "plasma torch" that generates a directed flow of plasma. Scrubber reduces the need for expensive gas filters designed to decrease the amount of pollutants released into the atmosphere. Slag is a glass-like bye-product, usually a mixture of metal oxides and silicon dioxide.

Plasmas Are All Pervasive

Plasmas also hold a great promise to realise our dream of producing energy from thermonuclear fusion, which is, incidentally, clean. We saw that plasma - the fourth (or the first!) state of matter forms over 99 per cent of the matter we come across in nature. But, producing plasmas in the lab itself is a challenge; and putting them to use for our benefit is an even greater challenge. Yet, plasmas find numerous applications in industry; and they enable technologies that are all pervasive in our daily life. Products from microelectronics, large area displays, lighting, packaging and solar cells to jet engine turbine blades and even biocompatible human transplants directly use or are manufactured using plasmas. Plasma etching can make smaller and sharper features on surfaces. The result is the improvement of our quality of life.

References

1. www.plasmacoalition.org : A wonderful resource with popular articles on various aspects of plasma science.
2. Encyclopaedia Britannica : Article on plasma physics
3. www.howstuffworks.com
4. Several Articles in Wikipaedia

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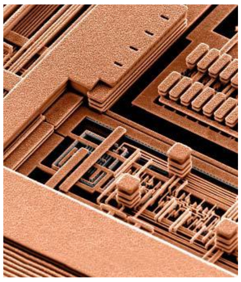
Chips and Plasmas

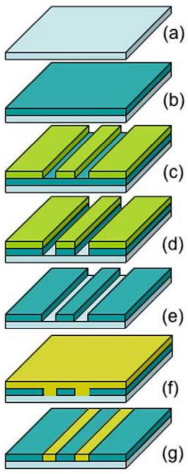
World Runs on Chips

Today's world runs on electronic chips. Think of any electrical device, and the chances are that it would be relying on an electronic chip. Most of the gadgets we use everyday – computers, cars, television sets, radios, even cars and microwave ovens have chips inside. And what is interesting is the fact that we cannot manufacture these chips without using plasma. How is that? It is due to the fact that plasma technology can form transistors and wires that are much smaller than the width of a hair! If it were not for plasma, the transistors would have to be made much bigger. It would not only make the chips more expensive, but slower and hence less powerful.



Wiring on a chip: the smallest wires are more than 100 times thinner than a single hair
(Image: International Business Machines Corporation)

At companies like Intel and Samsung, scientists and engineers utilise the unique properties of plasma to make computer chips, making plasma indispensable to the success of the information age. One can produce plasma by taking any ordinary gas, say, air and adding energy until electrons are stripped from the gas atoms and molecules. Usually electricity is used to strip electrons from atoms and molecules and produce plasma. The electrons become very hot, say, over 12,000 ºC! These hot (energetic) electrons collide with gas atoms and molecules, breaking many of them apart and knocking off electrons and produce electrically-charged particles called ions. One of the most common examples of plasmas is the fluorescent light. When we switch off a fluorescent tube light, it is filled with argon gas and mercury. When we turn the power on, the gas inside the tube is converted to glowing plasma! Plasma is also used to make computer chips. However, let us understand how chips are made.



Stages of Computer Chip Manufacture

Chips Resemble a Layered Cake

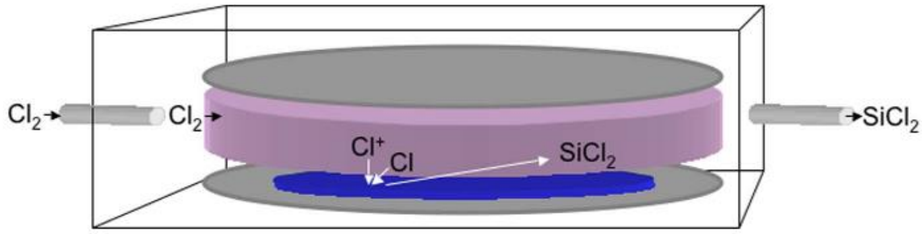
Chips resemble a layered cake – only the unwanted parts of each layer are removed before the next layer is applied. How is a complex, three dimensional chip-structure is made layer-by-layer? Initially a thin layer of material is added and then unwanted parts are removed. This process is repeated many times. To begin, we use a flat piece of silicon (a). A thin layer of glass is added to the entire wafer as shown in (b). Next, a layer of light-sensitive film (photoresist) is applied to the wafer. Laser light is used to remove parts of the film. The remaining film is called a mask (c). It protects parts of the wafer's surface from being removed during the "etch" step (d), which is really the plasma process we shall discuss below. Incidentally, etching implies carving or engraving

Once the etching is complete, the mask is stripped away (e). Next, a thin film of metal is deposited on top of the wafer (f). Finally, the extra metal is polished from the wafer, leaving a layer of metal wires and glass insulation (g). More glass is added to coat the top of that layer, and the entire process is repeated over and over, creating an intricate three dimensional network of circuit wiring. Connections between layers are made by etching small holes in the glass and filling the holes with metal.

Plasma in Fabrication of Chips

Chips are thus made by depositing thin layers of glass and metal, then removing the parts of each layer that are not needed for the final chip. But how is plasma used in this process? Some of the ions and parts of molecules in the plasma react chemically with the wafer surface. These reactive components of plasma are what make it possible for engineers to create the intricate layers of a chip.

Let us see how a silicon wafer is etched using plasma. The silicon wafer is placed in a vacuum chamber between two metal plates. The gas between the plates is removed by a vacuum pump and a small amount of chlorine gas is allowed into the vacuum chamber. The metal plates are connected to a high voltage source that turns on and off about 10 million times per second. The high voltage on the plates causes the chlorine to become electrically charged, and a glowing plasma is formed directly above the wafer. The chlorine molecules are broken apart by the plasma into chlorine atoms (Cl) and ions (Cl^+). These fragments attach to the silicon atoms at the surface of the wafer and create SiCl2 gas. This gas is pumped out of the plasma, removing silicon atoms in the process. A pre-patterned photoresist mask is used to protect portions of the silicon surface from Cl atoms, preventing specific regions of the wafer from being removed, as shown in steps (c) and (d) above.



A schematic of a silicon wafer (blue) in a vacuum chamber between two metal plates (gray). The plasma is shown as purple.

Depositing Thin Films on a Wafer Using Plasmas

To produce a chip, it may often be necessary to *deposit* thin films on a wafer. Now this process would be *opposite* of etching. To deposit solid material on a wafer, the input gas must contain the atoms of the element to be deposited. For example, silane gas (SiH_4) can be used to deposit silicon using plasma. Electrons in plasma break SiH_4 into silicon and hydrogen atoms. The silicon sticks to the surface of the wafer, and the extra hydrogen is pumped from the plasma. Within a few minutes, the silicon atoms accumulate to form a solid film of material across the entire wafer. This uniform layer of silicon then needs to be patterned with photoresist and etched to form useful devices. We may note that instead of SiH_4, we may have a different compound SiHx, where x can have different values representing different molecules. In a large commercial manufacturing environment, the wafers are handled by robots, not humans.

Chips Forty Years Ago and Today

How did they make chips some forty years ago? Indeed, many of these manufacturing steps used liquid chemicals or hot gases instead of plasma. Simple acids were used for etching. Because acids etch not only into the wafer but also under the mask, it is impossible to use acids to etch very small circuit patterns. Plasma, on the other hand, can etch straight into the wafer because the ions are accelerated straight from the plasma to the wafer by the high voltage used to energize the plasma. This is how the chips have become more sophisticated, and the size of the transistors has also become extremely small. Further, plasmas create far less hazardous waste than chemical processes, and thus plasma-based manufacturing is much less damaging to the environment.

We have considered just two examples of how plasmas help create electronic chips. Indeed, plasmas are used within the lasers needed to pattern the photoresist, and they are also used to strip the photoresist from the wafer. Plasmas can also create dopant ions that modify the electrical properties of silicon, thus creating transistors. Today, about half of the manufacturing steps used to make a computer chip rely on plasma. It is for these vital plasma technologies that today's modern technologies and gadgets have become possible.

References

1. http://www.plasmacoalition.org. a highly resourceful website on plasmas and their applications.

2. "Computer Chips and Plasma" by Jeffrey Hopwood (ibid.). The present article draws heavily on this article.

3. Image Courtesy: Microfabrication Laboratory, Northeastern Universirty;

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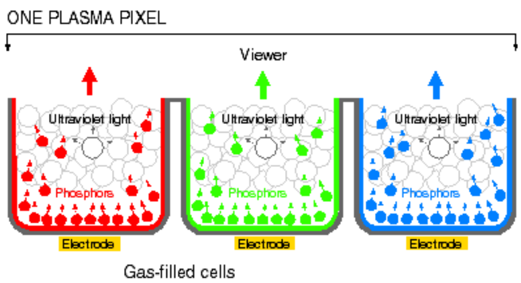
Plasma Display Panels

What Is a Plasma Display Panel?

Large screen plasma displays and flat panel plasma television sets have become quite popular in recent times. However, for many people, the word plasma implies only display screens. True, the plasma displays are very impressive, but, the word plasma really refers to a state of matter that resides not only inside those display panels, producing their light and images, but also in many other devices we use every day! Indeed, plasma is a gas containing a large number of electrically charged particles, both negatively-charged electrons and positively-charged atoms, called ions. In most plasmas, there are a large number of uncharged particles (called “background gas”) as well. Plasma fills most of the universe around us. The plasma in a display panel, however, is much like the plasma in another familiar device, the fluorescent lamp.

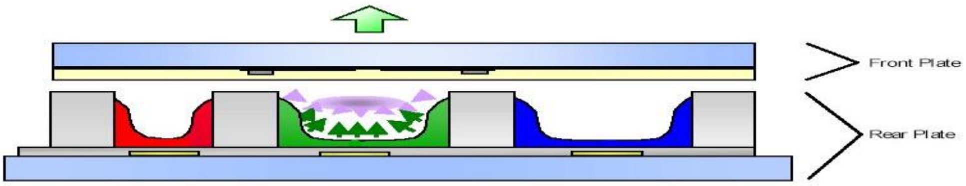
Today's PDP with up to 80" diagonal screens and millions of individual colour elements.

What is a plasma display panel (PDP) anyway? A plasma display panel (PDP) is essentially a collection of very small fluorescent-type lamps, each a few tenths of a millimetre in size. If we look closely, it is easy to distinguish the individual PDP cells – the tiny colour elements of red, green and blue light that together form what is called a *pixel*. The red, blue and green elements are called subpixels. As in a fluorescent lamp, the light we see does not come from the plasma directly, but rather from the *phosphor coatings* on the inside walls of the cells when they are exposed to ultraviolet (UV) radiation emitted by the plasma. Because each cell emits its own light, a plasma display panel is called an “emissive display.”



An individual plasma pixel
(Source: scvitalspeed.hubpages.com)

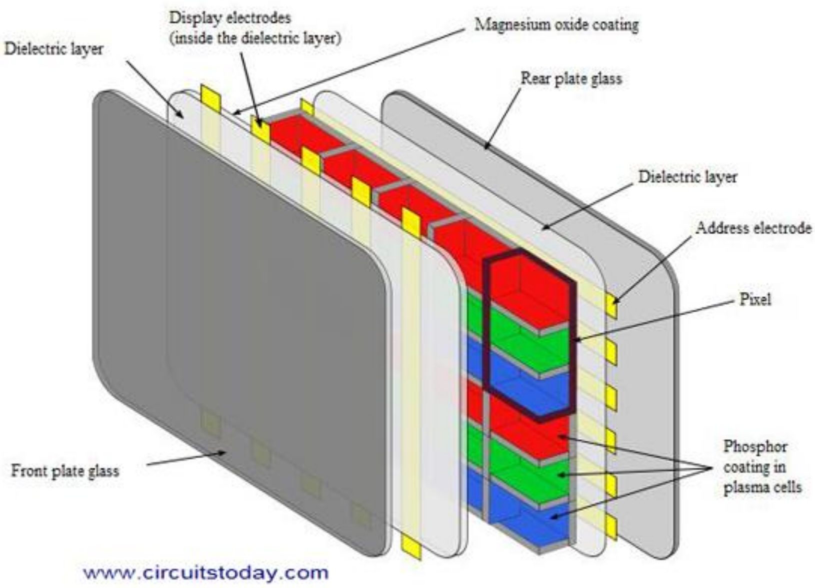
But, how does it differ from the familiar liquid crystal display (LCD)? Liquid crystal display (LCD), is also a type of flat display, but it has light coming from a lamp (actually a plasma lamp!) behind the liquid crystal, which has arrays of small switches controlling where light is allowed to pass through.



Address electrode causes gas to change to plasma state. Gas in plasma state (emitting UV) reacts with phosphors in discharge region. Reaction causes each subpixel to produce red, green, and blue light (source: www.ee.buffalo.edu)

How a Plasma Display Panel Works

For producing plasmas, we require a source of energy. As in fluorescent lamps, the plasma in a PDP is produced by applying a voltage across a gap that contains gas. The address electrodes cause the gas to change to a plasma state. The plasmas used in PDPs are considered *cold* plasmas in the sense that the background gas stays relatively cold while the electrons (and ions) in the plasma are heated by the applied voltage. When the hot electrons collide with the background gas atoms or molecules and transfer energy to them, many of those atoms respond by emitting UV radiation. The operating conditions of the display (gas composition, pressure, voltage, geometry, etc.) represent a compromise, taking into account performance requirements such as low voltage operation, long life, high brightness and high contrast.



A plasma display unit (schematic)
(Source: www.corcuitstoday.com)

The plasma display itself is a simple device. It consisting of two parallel glass plates separated by a precise spacing of some tenths of a millimetre and sealed around the edges. The space between the plates is filled with a mixture of rare gases at a pressure somewhat less than one atmosphere. Parallel stripes of transparent conducting material with a width of about a tenth of a millimetre are deposited on each plate, with the stripes on one plate perpendicular to those on the other. These stripes are the "electrodes" to which voltages are applied. The intersections of the rows of electrodes on one side and the columns of electrodes on the opposite glass plate define the individual colour elements – or cells – of a PDP. For high quality colour images, it is important to keep the UV radiation from passing between cells. To isolate the individual cells barriers are created on the inside surface of one of the plates before sealing. Troughs, honeycomb-like structures and other shapes have been used. The red, green and blue phosphors are deposited inside these structures.

Examples of the barriers that isolate each cell. The distance between the walls of each cell is a couple hundred micrometers – or about ten times the diameter of a human hair
(Source: www.plasmacoalition.org)

An important feature of PDPs is that the plasma in *each individual cell* can be turned on and off rapidly enough to produce a high quality moving picture. (To help turn the individual cells on and off, there are actually two electrodes on one side and a third electrode on the opposite side of each cell.) Earlier, switching the cells on and off cheaply and efficiently was difficult. However, because of advances over the past couple of decades in the miniaturization and efficiency of electronics, it has become a routine matter.

A Commercial Plasma Display Panel

A commercial panel consists of several million cells which have to be switched at a rate that will create 60 TV picture frames per second. A computer translates an image into a sequence of “on” and “off” voltage pulses which are applied to the electrode arrays *line by line and row by row* to select individual cells. Such control is possible because the plasma is fast and can respond to the voltage pulses in a millionth of a second. The complexity increases significantly when we consider that each small picture element, or pixel, consists of three colour cells, and each colour cell can display 256 intensity levels. Thus each pixel can display over 16.7 million (or, more exactly, 256x256x256) colours! Variation in light intensity from a particular cell is not accomplished by changing the voltage or the current through the cell. Rather, it is achieved by changing the length of time that the cell is “on” during one TV frame. Since the eye response is slower than the TV picture frequency, it perceives different colours depending on *how long* each cell is “on”. We may state here that almost every company engaged in the development and manufacture of PDP has made its own contribution to the switching systems to improve efficiency, speed, and performance.

A Journey of Fifty Years

Indeed, many years of research and development as well as major advances in electronics and manufacturing techniques have led to the plasma display panels we see in the market today. It is interesting to note that the plasma display panel itself was invented in 1964 by scientists at the University of Illinois, USA, with the first PDPs being only monochrome (single colour) displays. Research on multi-colour PDPs was going strong in the 1980s, and the first commercially available colour displays appeared in the late 1990s. It is now possible to manufacture PDPs with diagonals as large as 80 inches (200 cms) and with a thickness of only 3 to 4 inches (8-10 cms). Considerable progress has also been made recently to reduce the power consumption and increase the efficiency and life-time of PDPs.

The Challenge Ahead

Large screens, excellent image quality and brightness, and greater than 160° viewing angle characterize today's plasma panels, which are perfectly flat and perform well even in bright environments. The challenge now lies in the manufacturers' ability to develop low cost PDP displays, which will define true commercial success. Significant reductions in costs have been realized over the last few years. New PDP designs and processes are being introduced all the time that are continuing to reduce production costs. The PDP is sure to be one of the predominant large-format displays of the future.

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Welding with Plasmas

Plasmas Hold the World Together

It is said that plasmas hold the world together. Perhaps it may sound like an exaggeration, but not quite! Most of the goods manufactured today depend of thousands metal to metal joints. Cars, ships, trains, aeroplanes, pipelines, hot-water systems, and even the metal framework of buildings, and bridges. Many of those joints are welded using plasmas.

We have been surrounded by plasmas ever since the big bang. How do we get the light from the Sun, stars, lightning and the Aurora Borealis (also called the Northern Lights)? All these lights are all produced by plasmas. It was Benjamin Franklin (1706-1790) who first studied lightning and concluded that it was composed of charged particles, much before we knew of the existence of electrons or other charged particles (ions). However, it is only recently, almost two and a half centuries later, that we have learnt to harness the power of plasmas to work for us. A plasma is a gas containing a large number of positively and negatively charged particles. Plasmas have the ability to concentrate and focus energy in many useful ways.

Plasma Arc

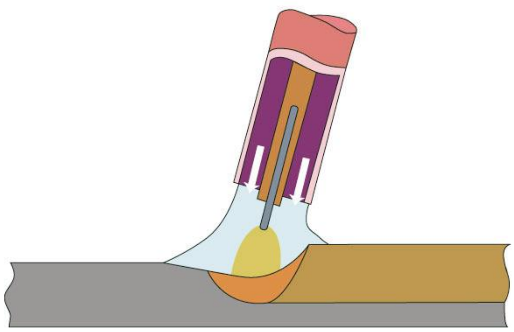
The first man-made plasmas consisted of spark discharges from static electricity. The first artificially produced high power plasma was generated by Sir Humphrey Davy (1778-1829) in the early 19th century. We may note that It was Humphrey Davy who coined the term “electric arc”. How did he coin the term? The bright light emitted in his laboratory formed an “arch” as the air heated by the electric current rose between the two horizontal electrodes! Yet it was not until the late 19th century that industrial uses of electrical arcs or plasmas became prevalent when electricity became readily available.

A welding helmet and flame retardant clothing protect a welder from sparks, heat and ultraviolet rays

Welding Arc

Because the electrons in plasmas move very easily, plasmas can carry very large electric currents and can concentrate the electric energy in a very small volume. This is how plasmas make very efficient sources of heat for melting metals. Today, large quantity steel produced is melted in electric arc furnaces. How much energy does a steel furnace electric arc concentrate the energy? In a country like India, the electrical energy concentrated may be sufficient to operate 1000 homes into a volume equal to that of a football; and can melt 100 tons of steel in half an hour! On a smaller scale, this same type of electric arc is used to weld metals together.

What is a welding arc? In arc welding, an electrode is connected to one end of an electrical power supply, and the metal to be welded is connected to the other end. The welder touches the tip of the electrode to this metal, and draws it away to produce a short gap, about a fraction of a centimetre in length or so, between the electrode and the metal. The voltage in the power supply causes an electrical current to bridge this gap. The current heats the air to create a plasma, which emits a very intense light. This is the welding arc. The welder must protect his eyes from the intense arc light by using the welding helmet that allows only a very small fraction of the light to enter his eyes.



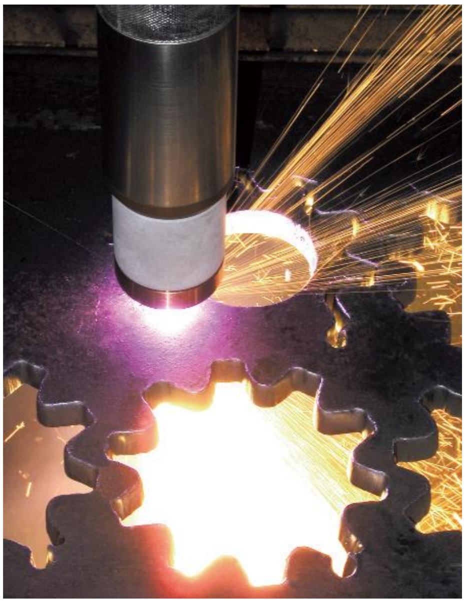
An electrical current bridges the gap between the electrode and the metal to be welded.

In a high power welding arc plasma, all the particles - electrons, positively charged ions and the remaining neutral atoms - are at nearly the same temperature. The plasma temperature may exceed 6,000° C. This temperature is far above the melting temperature of all known materials. For sure, *everything held in contact with this intense plasma melts or vaporizes*. The edges of the metal pieces to be joined melt forming a liquid pool. The tip of the electrode also melts, and the resulting liquid metal transfers across the arc to the weld pool as drops of liquid to combine with and enlarge that pool. As the arc is removed, the weld pool cools and solidifies to form a weld. The electrode material melted into the weld is called “filler” metal, as it fills the gap between the metals being welded. Hundreds of thousands of tonnes of filler metal are used each year to construct nearly all forms of bridges, buildings and transportation systems.

Electromagnetic forces in the arc produce a plasma jet - or plasma wind - at the tip of the electrode. The jet moves at a very high velocity, almost 800 kilometres per hour. The force of this plasma jet exceeds the force of gravity and carries the molten metal drops from the tip of the electrode into the weld pool. That force also creates a stiff arc, which allows the welder to direct the heat as the electrode is tilted and turned to any angle or position - even overhead! The jet also helps protect the liquid metal from oxidation by the surrounding air – and it pushes aside the melted weld pool, permitting deeper and stronger welds. The intense heat created by the plasma produces a pressure within the plasma that is high enough to counteract the pressure produced by over 100 metres of water. This allows arc welding to be performed deep under water for offshore oil rigs or even ship repair.

Cutting Metals

The plasma arc process has proved to be the fastest and most economical method of cutting virtually any metal. Let us see how. Most welding arc plasmas operate in the open atmosphere. However, an even stiffer and more intense arc can be produced by operating the arc in a small copper cavity which is cooled by either water or air. The plasma, which is heated and expands in this confined space, exits a small hole in the cavity with even higher velocities than an arc that is produced in the open atmosphere. This higher velocity and much stiffer plasma jet not only melts metal very quickly, but has enough force to blow the molten metal away, causing a very rapid cutting action. With nitrogen plasma, metal plates up to 8 centimetres thick can be cut at speeds up to 35 centimetres per minute. With oxygen plasma, 1 centimetre thick steel can be cut at 4 metres per minute! Thinner plates can be cut at over 6 metres per minute! We may note that in large production facilities, the cutting is done under several centimetres of water, eliminating smoke and fumes, thus making the plasma cutting process the most environmental friendly method of cutting metals.



Plasma can be used to cut through metals at high velocity

Plasmas Revolutionize Fabrication of Metal Structures

Plasma arcs, used for both welding metals together and cutting metals apart, have revolutionized the way we construct bridges, buildings, pipelines, energy generation facilities, cars, trucks, ships and airplanes. We can fabricate these and other metal structures more quickly, more safely, more economically, and in greater quantity and size than would otherwise be possible. These compact plasmas work more efficiently than anything else available and are being harnessed to create much of the man-made world around us.

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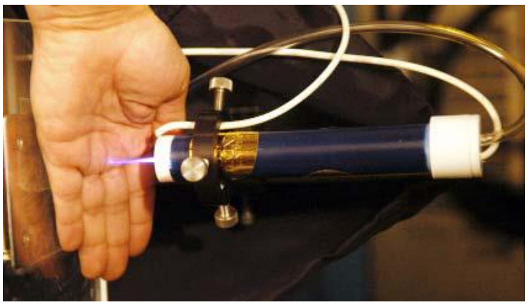
Plasmas in Medicine

Plasmas in Medicine

You must have experienced that in case of a cut or bleeding wound, it takes some time for the blood to coagulate, and the bleeding to stop. But, could you imagine blowing a cold breeze of helium on a bleeding wound and watching the blood coagulate at a rate faster than it normally would? And that the wound heals at a much faster rate? Surely, it sounds strange and far-fetched. But scientists with expertise in plasma science, microbiology, biochemistry, and medicine are working on making something like that actually happen! Well, they do not use helium *per se*, but rather helium in a plasma state.



A cold plasma in contact with skin without harming it, making it ideal for disinfecting wounds.

As we know, plasma is the fourth state of matter - the other three being the solid, liquid and gas. How can we produce a plasma? If a gas is heated or subjected to high electric fields, electrons already present are accelerated to high kinetic energies. When these electrons collide with the atoms and molecules of the background gas they are able to knock off and free more electrons. The atoms or molecules that are stripped of one or more electrons are called ions. Now, the newly freed electrons are accelerated by the applied electric field and collide with other atoms and molecules, and produce more ions and electrons. The mixture of neutral atoms and molecules, ions, and electrons is what is referred to as plasma. Plasmas can be very hot or very cold - like matter at the beginning of the big bang, or as in laboratory condensed matter. Medical plasmas are in the range that are hot enough to produce the reactive species of atoms and molecules needed for effective treatment, but cold enough to leave tissue unharmed!

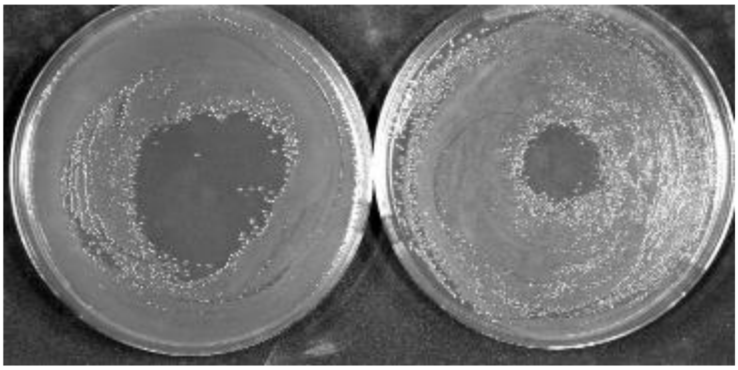
Plasmas and Living Tissues

In the last a few years, research on the use of low temperature plasmas in medicine has considerably intensified, and as a result, plasmas are poised to enter healthcare. Scientists have discovered ways to apply plasmas directly to living tissues to deactivate pathogens (any disease causing agents like bacteria, viruses or other microorganisms), to stop bleeding without damaging healthy tissue, or to disinfect wounds and accelerate wound healing; and even to selectively kill some types of cancer cells. How do the plasmas help treat these conditions? Plasmas produce chemically reactive atoms and molecules such as hydroxyl (OH) and atomic oxygen (O) that can kill harmful bacteria through oxidation. This is important because oxidation of the lipids and proteins that constitute a cell's membrane can lead to the complete disruption of the membrane.

Sterilizing Medical Equipment

Scientists have discovered that bacteria cannot cope with the harsh environment created by plasmas. They have found that bacteria died in large numbers in a matter of minutes or even seconds, depending on the strength of the bacterial strain. This property of plasma has been exploited to develop plasma devices that can be used to sterilize medical tools and instruments without the risk of damaging them.

Today, many medical tools are made from polymers that are heat sensitive and therefore cannot be sterilized by conventional means such as autoclaving. Incidentally, autoclaving uses hot steam at high pressures for sterilization purposes. Reactive plasma species of atoms and molecules near room temperature can rapidly kill bacteria, viruses and fungi deposited on the surfaces of surgical instruments and medical devices - including those made of heat-sensitive polymers. We may note that these plasma species are often maintained in a gas flow and can diffuse into structures that are narrow and difficult to access. These characteristics are common among instruments used for minimally invasive surgeries. The special properties of cold gas plasmas offer the prospect of protection from highly infectious agents such as prion, a structurally "misshaped" protein responsible for mad cow disease; and which is resistant to all commercial decontamination procedures.



Petri dishes of E. coli cells were exposed for 120 seconds to a cold plasma plume (left - helium + 0.75% O_2 and right - helium only). The dark zones in the centre are "kill zones," where bacterial cells were destroyed and not able to replicate / multiply

A Remarkable Property of Plasmas

Reactive plasma species appear to cause little or tolerable damage to living animal and plant tissues, and at the same time are capable of destroying bacterial cells. How is that? This is because bacterial and mammalian cells respond very differently to chemical and physical stresses - such as those experienced with cold gas plasma treatments. Consequently, skin fibroblast cells - cells from which connective tissues develop - are found to remain viable under plasma conditions, but are lethal to E. coli bacterial cells. This ability of plasma to destroy bacteria while leaving animal and plant tissue unharmed is key to the development of important plasma applications, including food decontamination, skin disinfection, and tumour reduction.

As in chemotherapy, cold plasma treatments appear to be able to induce programmed death (apoptosis) among cancer cells, and arrest the rapid proliferation of cancerous cells; and at the same causing very little damage to living healthy human tissues. Ultimately, the success of this approach will depend on finding the right recipes of reactive plasma species, and delivering them effectively to the complex environment of diseased sites in the human body. There is enough hope that cold gas plasma applications would be developed to solve some of these pressing medical challenges of today.

A Word of Caution

Here is a word of caution! Plasma can destroy pathogens at sufficiently high doses; however, at a low dosage it can also *accelerate* the multiplication of cells. This property is an important aspect in the wound healing process. We may, however, note that the ability of plasma to kill bacteria cells and to accelerate the proliferation of specific healthy tissue cells is known as the “plasma kill / plasma heal” process, and it has led scientists to investigate the use of cold plasma for wound care. In particular, chronic wounds, such as diabetic ulcers, do not respond well to conventional healing methods. Hundreds of thousands of amputations occur every year in India because present medical methods are not able to heal these types of wounds. Although plasma-based technology for wound care is still in the research phase, preliminary tests show signs of successful treatments of some types of chronic wounds.

Plasma can be used to control plaque, tooth decay, and periodontal diseases

Plasmas in Dentistry

Yet another exciting development is in the area of dentistry, where cold plasma has found applications. Plasma can be an effective method of controlling oral bio-films (commonly known as slime). It is essentially a highly organized, three-dimensional bacterial community; and it enables microorganisms to communicate, maximize resources, and also protect the integrity of the community! Dental plaque is one example of an oral bio-film. It is the primary cause of tooth decay and periodontal diseases such as Gingivitis (inflammation of the gum tissues); and periodontitis (inflammation of the periodontium - the tissue that supports the teeth). In a laboratory environment plasma has been shown to inactivate bacteria that cause tooth decay, and thereby control periodontal diseases. Plasma was found to reduce infection when it was applied to dentin (the calcified tissue structure underneath the tooth enamel). Plasma could potentially remove the infected tissue in the tooth cavity. Thus, one day plasma may replace the universally feared dentist's drill! These recent developments indicate that not too far in the future plasma-based devices could be available to dentists, allowing them to treat oral-borne diseases effectively, with little pain to their patients.

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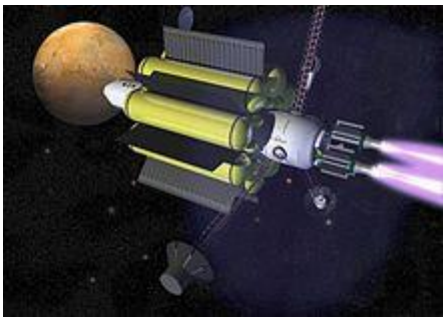
Propelling Rockets with Plasma

An early plasma propulsion engine from the Lewis Research Center in Cleveland, Ohio in 1961

Limitation of Today's Rockets

Many of us must have dreamed of going on a space travel to the Moon, Mars and the stars in our childhood. Space probes have already travelled to most of the planets and even beyond the solar system. India's Mars Mission also has reached the Mars recently. We have witnessed development of the space ships that could transport humans beyond Earth. Space travel in an orbit around the Earth has become almost a routine affair today; and after landing on the Moon nearly half a century ago, humans are now preparing to journey to the planet Mars.

And yet we do not have faster ships that can venture far out into the vastness of space. With current technology, even a visit to Mars, our nearest planetary neighbour, would take very long in the fragile and small spacecraft that we have. What difficulties would the travellers encounter? Besides taking more than six months of time to reach the Red Planet, they would experience debilitating weightlessness and persistent radiation. Their bodies and minds would suffer considerably during the journey.



A Mars mission as it might look in the future, driven by a plasma rocket and powered by nuclear reactors.

Many of these difficulties are the result of the limitations of today's chemical rockets. Despite remarkable technological advances over the decades, the fuel consumption of those rockets is still so high that *only a tiny fraction of the ship manages to reach its final destination*. For example, we need gigantic external fuel tank to bring the space shuttle to an orbit only a few hundred kilometres up. A trip to the Moon would require a much greater amount of fuel - and a manned trip to Mars would require even more.

Plasma Rockets – A Better Alternative

What could be the alternative then? In this context, plasma rockets open up new and exciting possibilities for fast space transportation. Developing rocket engines in which ionized particles are accelerated by electric and magnetic fields would greatly expand the range of rocket propulsion far beyond the limits of the chemical rocket. Further, the fuel consumption would be very much lower. Indeed, many plasma rockets have been under development for years and some are already in limited operation.

We may note, however, that plasma rockets are dependent upon the availability of electric power, which is still limited in space. This is because electricity is generated mainly by solar arrays in space. Because of this, plasma rockets have evolved over time only as low-power devices which are not really suitable for long-distance transportation and human space flight. However, this picture is rapidly changing. Advances in solar technology have increased the available electrical power, and this breakthrough has opened up new and exciting possibilities for high-power plasma propulsion. In addition, renewed interest in nuclear power for space missions far from the Sun is creating a new possibility for high-power plasma rockets.

Rocket Propulsion

How does a rocket propel itself? As we know, the basic principle of rocket propulsion is based on the Newton's third law of motion, or the law of action and reaction. A rocket propels itself by expelling material at high velocity in the opposite direction to its motion. This material is usually a gas. Heat from a chemical reaction generally imparts the velocity. The heat builds pressure in a combustion chamber and is converted to exhaust velocity by the action of a properly designed nozzle. Now, we can achieve the same thrust by either ejecting more material at low velocity or less material at high velocity. We must, however, remember that the material has to be carried on board. Hence the latter approach is preferred, i.e. ejecting less material at high velocity. In order to minimize the amount of material carried, one seeks to achieve the highest possible exhaust velocity. Exhaust velocities far beyond the reach of chemical rockets can be achieved by using plasma, in which atoms of the exhaust gases have been stripped of some of their electrons, making it a soup of charged particles.

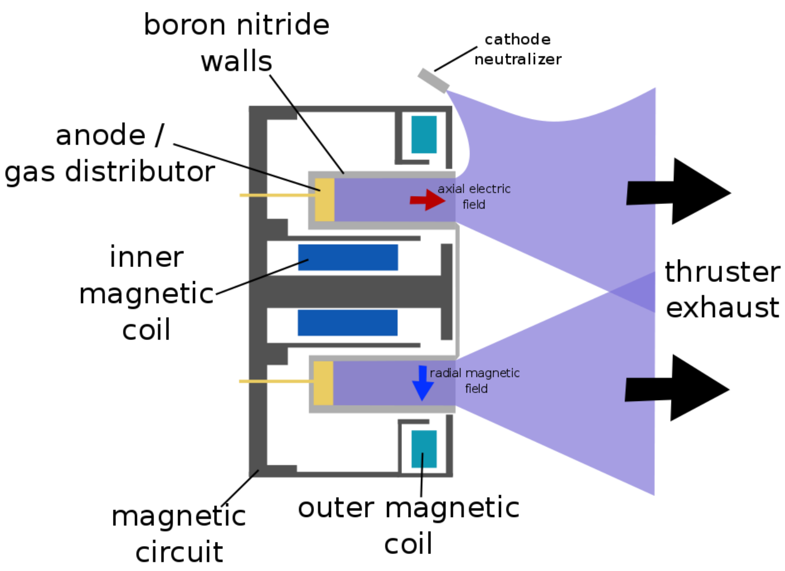
Plasma Rockets

The temperature of a plasma in a fluorescent tube is about 12,000 ^{0}C. But present day laboratory plasmas can be a thousand times hotter. Particles in those hotter plasmas move at velocities exceeding 300 kilometers per second. These temperatures are comparable to those in the interior of our Sun. No known material could survive direct contact with such plasma. However, plasmas respond well to electric and magnetic fields. A magnetic channel can be constructed to both heat and guide a hot plasma so that the plasma *never* touches the material walls.

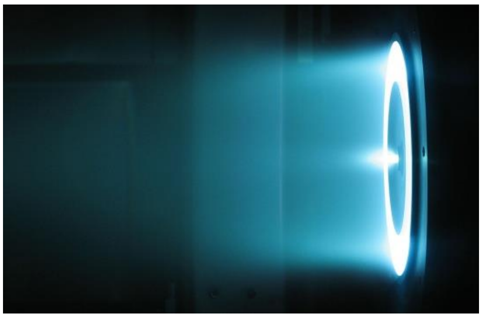
How do we meet the energy requirements for travels beyond Mars? As the exhaust velocity increases, power requirements increase very rapidly. While solar power remains viable for robotic cargo missions in the Earth-Moon environment, for human transportation it is difficult to envision any other option than nuclear electric power. This is especially true for missions beyond Mars, where the power of the Sun is relatively low.

Plasma Rocket Engines

A number of low-power plasma rockets are already in use. The best known and oldest technology is the *Ion Engine*, which uses a metal grid to extract and accelerate ions from a relatively low temperature and low density plasma discharge. The ion jet must be neutralized by a spray of electrons ejected from a neutralizing gun at the rocket exhaust; otherwise the spacecraft would build up a negative electric charge that would ultimately pull the ions back in. Ion engines produce exhaust velocities up to 70 kilometers per second using Xenon propellant.



Hall Thruster : Hall thrusters are largely axially symmetric. This is a cross-section containing that axis.



6 kW Hall thruster in operation at the at the NASA Jet Propulsion Laboratory

A variation of the ion engine is the *Hall Effect Thruster* that combines a strong localized static magnetic field perpendicular to the electric field created between an upstream anode and a downstream cathode called neutralizer, to create a "virtual cathode" (area of high electron density) at the exit of the device. This virtual cathode then attracts the ions formed inside the thruster closer to the anode. Finally the accelerated ion beam is neutralized by some of the electrons emitted by the neutralizer. This technique reduces the erosion and heating of rocket components that are directly exposed to plasma bombardment, a major problem in plasma rocket engineering. The plasma density in ion and Hall thrusters is generally low due to physical constraints. Therefore, their power density is also low. This implies that high-power systems of those types would need to be physically large. The low-power Hall Effect Thruster is presently being used in commercial satellites for small “station keeping” maneuvers, that is, for maintaining the satellite’s position.

For primary propulsion, considerable research is being carried out on alternate high-power radio-frequency-driven systems. One such concept is VASIMR. This engine can operate with a number of alternate gases and does not rely on rare and expensive propellants such as Xenon. In this engine, ions are guided and accelerated out the nozzle by magnetic fields. VASIMR works by using radio waves to ionize a propellant into a plasma and then a magnetic field to accelerate the plasma out of the back of the rocket engine to generate thrust. Although many other plasma thrusters are under development at present, all have comparative advantages and disadvantages, and intensive research is currently underway to test and deploy them.

Other system under development is the *Magneto Plasma Dynamic Thruster* (MPD), which uses the Lorentz force - force resulting from the interaction between a magnetic field and an electric current - to generate thrust.

Plasma Rocket Engines: Promise for Tomorrow

Plasma engines hold a promise to help long-distance interplanetary space travel a distinct possibility. Further, plasma rockets could be valuable in a number of ways. For example, low-power rockets could play an important role in maintaining the orbits of space stations. With sufficient available power, a plasma engine could also be used to nudge an incoming asteroid away from a collision path with Earth. Indeed, in the more distant future, fusion-driven plasma rockets could be instrumental in carrying us far beyond our fragile planet. It might even help ensuring the survival of the human species.

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Cleaning the Environment with Plasmas

Clean environment: A Major Challenge

Saving the natural resources has become a major challenge today. Water, air and soil, the essential resources on which the life on Earth depends, have suffered enormously from the effects of industrial waste and pollution. This has resulted in making quality of our environment a burning issue for of all time. To reduce the effects of emission of greenhouse gases from factories and automobiles, and the concerns of global warming, scientists the world over have been developing new ways of improving the environmental quality. One approach is to use the plasmas for the purpose.

Now, a word about plasmas! While solids, liquids and gases have no electrical charge, plasmas contain freely moving ions (positively charged atoms or molecules) and electrons, which are negatively charged particles. The plasmas can transform pollutants into environmentally safer materials. This transformation can occur through heating or through interactions involving particles that are *not* available in normal gases.

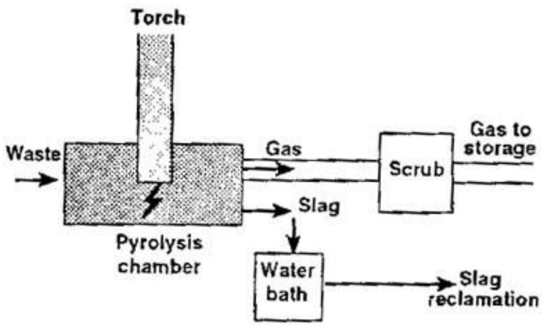
Processing Pollutants using Plasmas

How can the pollutants be processed efficiently using plasmas? Plasmas generally operate at about atmospheric pressure in such applications. We may note that this is a relatively high pressure for plasmas! This is in view of the fact that pressures required in most plasma applications like fusion energy and manufacture of computer chips are much lower - near vacuum conditions! Imagine a naturally occurring plasma process like a bolt of lightning taking place at atmospheric pressure, and you can get some idea of how difficult it would be to control and use man-made plasmas at atmospheric pressures! Indeed, we need to master this difficulty to help lead to a cleaner environment! When operated in what is called “thermal mode”, particles in the plasma (electrons, ions and neutral atoms or molecules) get uniformly hot. In plasmas the temperature of the charged and neutral particles can become much higher than is possible with incineration (burning something completely with conventional means), and so they can destroy waste more thoroughly.

An incinerator requires large amounts of air to burn wastes. On the other hand, a high temperature thermal plasma requires little gas flow because no air or oxygen is required for producing a high temperature. As a result, plasma furnaces could be used instead of conventional incinerators to process organic or hazardous municipal or medical waste more thoroughly and with significantly *less* combustion exhaust. There is one more advantage. Plasmas reduce the need for expensive gas filters (commonly called “scrubbers”) designed to decrease the amount of pollutants released into the atmosphere. Most important, the plasma process eliminates ash, which in present municipal or hospital incinerators is considered hazardous. Rather than producing ash, high-temperature plasmas in arc furnaces convert materials into a glassy substance, separating out the molten metal at the same time, which can then be recycled. The stable glassy material can be used in landfills with essentially no environmental impact, since it cannot percolate into the soil.

Plasma Pyrolysis

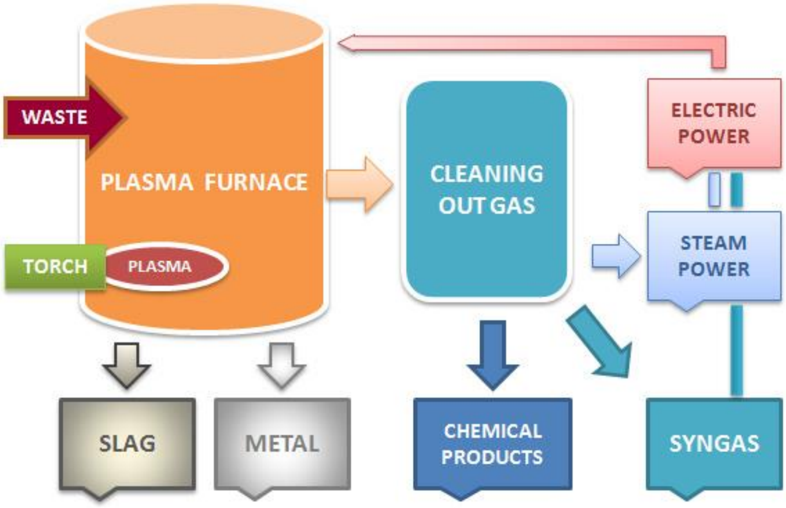
Plasma furnaces using "plasma pyrolysis" technique are being used in many countries in including India to treat a variety of wastes, say, hospital waste, and waste produced by organic, and rubber products; and wastes produced by plastics and residues from other petroleum products. In plasma pyrolysis, generation of heat is independent of chemistry of material used. It is fast heating, 5000 ^{0}C can be achieved in milliseconds. It is fast quenching and consumes small quantity of gas. In pyrolysis plants for treating hospital wastes, the high ultraviolet radiation flux destroys pathogens. Waste produced could be dry or wet, which needs to be treated. It is possible to recover energy in the form of carbon monoxide and hydrogen. FCIPT of the Institute for Plasma Research, Gandhi Nagar, Gujarat, has developed Plasma Pyrolysers for treating wastes of different kinds using plasma technology.



Plasma Pyrolysis (Schematic)
(Source: cO3.apogee.net)

Plasma Gasification

Gasification is a process in which materials are exposed to some oxygen, but not enough to allow combustion to occur. Temperatures in gasification are usually above 750^{0}C. In some systems, the pyrolysis phase is followed by a second gasification stage. This is with a view that more of the energy carrying gases are liberated from the waste. The main product of gasification and pyrolysis is syngas (synthetic gas), which is composed mainly of carbon monoxide and hydrogen (85 per cent), with smaller quantities of carbon dioxide, nitrogen, methane and various other hydrocarbon gases. Syngas (synthetic gas – a mixture of hydrogen and carbon monoxide) can be used as a fuel to generate steam or electricity as a basic chemical feedstock in the petrochemical and refining industries. The calorific value of this syngas will depend upon the composition of the input waste to the gasifier.



Plasma Gasifier
(Source:www.httcanada.com)

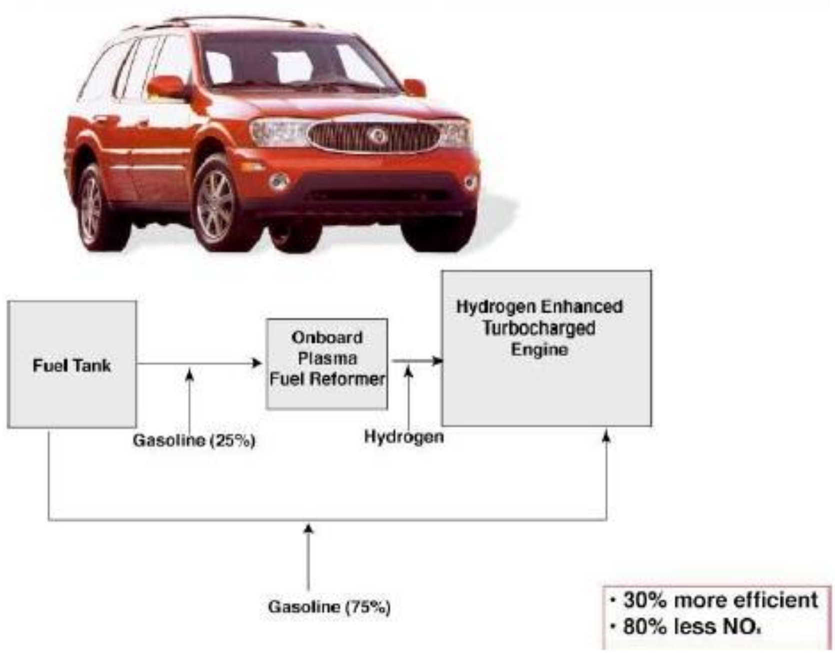
Monitoring Environment with Plasmas

Plasmas (both thermal and non-thermal) can be used to monitor environmental pollution with high sensitivity in air and smoke stacks. Plasma generated in a smoke stack excites trace elements in the smoke to make those elements emit light. Using a spectrometer, an operator can identify the elements and determine quantities of the pollutants. Such pollution monitors have demonstrated sensitivity of better than one part per billion for lead, chromium, beryllium, mercury, and other pollutants, allowing better control of hazardous air pollution.

Plasma can be used to clean and monitor smoke stack emissions

Reducing Pollution from Transport Vehicles

Plasmas can also be used in vehicles to reduce pollution from conventional fossil fuel combustion by “reforming” the fuel before it is burned, breaking it down into compounds that burn more cleanly. Work is under progress on a “plasmatron,” a miniature high voltage thermal plasma that helps separate the hydrogen atoms from complex organic molecules. This device can be used to reform hydrocarbon fuels, such as petrol, into cleaner burning hydrogen or syngas.



High efficiency automobile engine of the future using plasma-hydrogen enhancement (Source: www.windsofchange.com)

Controlling Soil Pollution

Contamination of soil also can be controlled using plasma processing. High temperature plasmas can process solid wastes and chemical spills in soil, destroying toxic compounds or converting them to safer forms. Research is being carried out in this regard at several places in the world.

Controlling Water Pollution

Some low-pressure plasmas can emit large amounts of ultraviolet (UV) radiation, X- radiation or electron beams through windows into the atmosphere. These plasmas can be used for a variety of environmental needs. For example, intense UV radiation can disable the DNA of a microorganism in water, thereby making it impossible for that microorganism to replicate. This plasma-based UV method takes only few seconds, has no effect on the taste or smell of the water, and is effective against all known water-borne bacteria and viruses. This technique is being used in Bangladesh, where it has been demonstrated that surface water (in ponds and shallow hand-pumped wells) could be used for drinking once it was decontaminated with UV radiation, eliminating microorganisms carrying water-borne diseases such as cholera. Intense UV water purification systems are especially important for developing countries since they can be easy to use and have low maintenance, high production and low cost. Plasma-based UV water treatment systems use several thousand times less energy than boiling water!

Improving the Quality of Life

There is no gainsaying the fact that developing and implementing plasma technologies could help clean up and protect our environment. These technologies can also provide new cleaning methods, and prevent reducing pollution, and improve the quality of life in developing countries. They may provide the only solutions to many of our environmental challenges. Once developed, these technologies could make air, water and soil that have become the global garbage cans of today a thing of the past.

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Energy from Nuclear Fusion

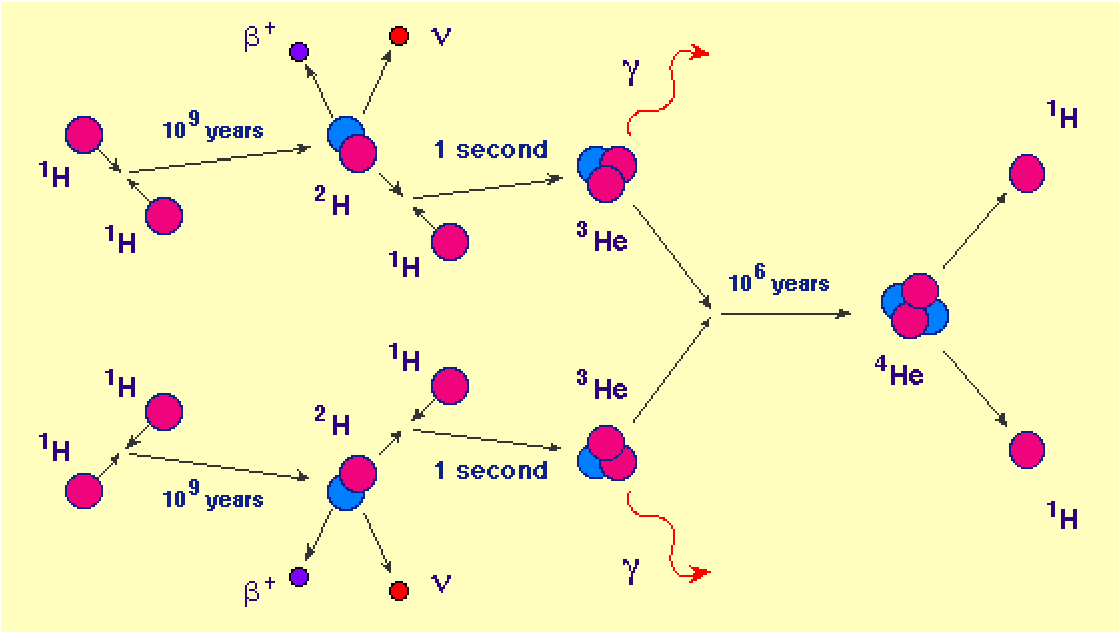
Fission and Fusion

When a heavy nucleus, say uranium-235 (U^{235}), is bombarded with neutrons, it could absorb a neutron and split into two roughly equal parts releasing energy. This process is called *nuclear fission*. Conversely, energy could also be released if two light nuclei are combined to form a nucleus of somewhat larger mass number. The heavier nucleus thus formed has a mass *less* than the light nuclei taken together before the reaction. This mass defect (difference) appears as energy in accordance with the mass-energy relation of Einstein. This process is called *nuclear fusion*. This process, however, is hindered by the mutual Coulomb repulsion that tends to prevent two such positively charged particles from coming within the range of each other's nuclear forces and "fusing". It turns out that for two deuterons (^2H), the energy required for each particle to penetrate this Coulomb barrier is about 200 keV. How to attain such high energy to achieve fusion? At room temperature, the mean thermal energy of a particle is only about 0.04 eV! The best way to obtain fusion in bulk matter would be to raise the temperature of the material, so that the particles have sufficient energy to overcome the Coulomb repulsion due to their thermal motions alone. This process is called *thermonuclear fusion*.

At room temperature, the mean thermal kinetic energy of a particle being quite small, we do not expect the fusion reaction to take place. Even at the centre of the Sun with a temperature of about 1.5×10^7 K, the mean thermal kinetic energy is only about 1.9 keV, which is again far too less than 200 keV barrier. And yet we know that thermonuclear fusion not only occurs in the solar interior, but is its central and dominant feature. How does the nuclear fusion reaction proceed in the Sun's interior, then? Although 1.9 keV is the *mean* thermal kinetic energy; particles with much greater energies than this mean value are also present, though in small numbers. Further, it is also possible for the particles with kinetic energies below the barrier energy to "tunnel" through the barrier to a significant level - a purely quantum mechanical phenomenon! It is through these processes that fusion reaction takes place in the interior of the Sun.

Nuclear fusion and energy production in stars

The Sun radiates energy at the rate of 3.9×10^{26} W, and has been doing so for about 4.5 billion years! It has been known since the 1930s that thermonuclear fusion processes in the Sun's interior account for this enormous energy output. The Sun's mass is 2.0×10^{30} kg. What fusion reaction is responsible for generating the Sun's energy? The Sun's energy is generated by the thermonuclear *burning* (or *fusing*) of hydrogen to form helium. It is accomplished through what is known as the *proton-proton (PP) cycle*, as shown in the figure.



The proton-proton (PP) cycle that primarily accounts for energy production in the Sun

Let us briefly describe the proton-proton (PP) cycle. Two protons (^1H) undergo a simultaneous fusion and beta decay to produce a positron, a neutrino, and a deuteron (^2H), or a heavy hydrogen nucleus. The positron, incidentally, very quickly encounters a free electron in the Sun, and both particles annihilate. Their rest energies appear as two gamma rays. The deuteron reacts with another ^1H to produce a nucleus of helium with two protons and one neutron ($^3He_2$) and a gamma-ray. Then, two $^3He_2$ nuclei produced in two separate events fuse to form a $^4He_2$ nucleus plus two protons. *The net effect is to convert hydrogen to helium*, with the energy released going into the particles and gamma-rays produced at each step of the sequence. We may note that we started with two protons; and at the end of the process, we were left with two protons and a helium ($^2He_4$) nucleus.

The average time required for a nucleus to undergo each step of this sequence in a typical stellar interior is indicated in the figure. Thus, for example, a hydrogen nucleus waits on the average 1 billion years before it undergoes an interaction with another hydrogen nucleus to initiate the sequence! Since all other steps require much less time than this, it is this initial step that controls the rate of the reaction. This incredibly small rate nevertheless accounts for the luminosities of normal stars because there are so many hydrogen atoms in the core of a star that at any one instant many are undergoing the reactions of the PP chain.

How much is the energy produced in each PP cycle? Taking an overall view of the PP cycle, we find that it amounts to the combination of four protons and two electrons to form an alpha particle ($^4He_2$ nucleus), two neutrinos (*v)* and six gamma rays (γ):

$$4\ ^1H + 2e \rightarrow\ ^4He + 2v + 6\gamma$$

Let us add two electrons on both the sides. Then we shall have,

$$4(^1H + e) \rightarrow (^4He + 2e) + 2\nu + 6\gamma$$

The quantities in the parenthesis now represent atoms, and not bare nuclei, of hydrogen and helium. The energy released Q now can be easily calculated using the atomic masses of hydrogen and helium, as follows:

$$\begin{aligned} Q &= \Delta mc^2 = [4m\,(^1H) - m\,(^4He)]\,c^2 \\ &= [4(1.007825\text{ u}) - 4.002603\text{ u}]\,c^2 \\ &= 26.7\text{ MeV.} \end{aligned}$$

Neutrinos have quite negligible mass and gamma-ray photons have no mass, hence do not enter the calculations. The two neutrinos produced in each cycle carry 0.5 MeV of this energy, and being highly penetrating, escape the Sun. Hence 26.2 MeV per cycle is the energy available within the Sun.

How long can the Sun continue to shine at the present rate before all the hydrogen has been converted to helium? Hydrogen burning has been going on for 4.5 billion years, and there is enough hydrogen left for about 5 billion years more! Then the major changes will begin to occur. The Sun's core, which will mainly be helium then, will begin to collapse and to heat up while the outer envelope will expand greatly, and may even swallow the Earth's orbit! The Sun will then become what the astronomers call a *red giant*.

The PP reaction produces a helium nucleus. How about the synthesis of heavier elements? As the star evolves and becomes still hotter, other elements can be formed by other fusion reactions. However, elements heavier than A=56, say, iron (^{56}Fe) cannot be manufactured by further fusion processes. Elements heavier than ^{56}Fe can be formed in *supernova* explosions, when a massive star 8-10 times heavier than the Sun explodes. But then how do we find elements heavier than iron on the Sun? The Sun (along with the planets) was formed from the debris of a supernova explosion that contained those elements, and that is how we find those elements on the Sun - and on the Earth.

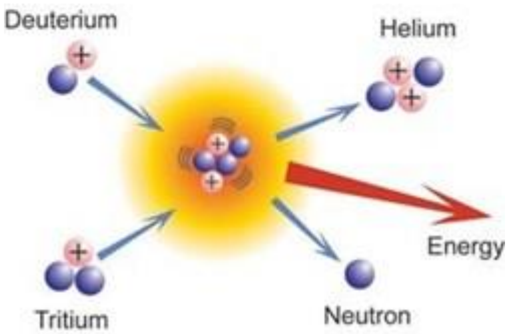
Controlled thermonuclear fusion

We already have many reactors that produce energy through nuclear fission. But, could we build a reactor to produce energy through controlled thermonuclear fusion? We have large amounts of hydrogen stored in the seas and oceans in the form of water, and hence a vast potential for producing energy through fusion. True, the prospects do look attractive! Fusion reactions have indeed taken place on Earth only since October 1952, when the first fusion (or hydrogen) bomb was exploded. The high temperatures needed to initiate the thermonuclear reaction in this case were provided by a fission bomb used as a trigger. However, a sustained and a controllable thermonuclear power source, a fusion reactor, has proved to be much more difficult to achieve. The goal, however, is being vigorously pursued as many perceive it as the ultimate power source of the future, at least as far as the generation of electricity is concerned. The proton-proton interaction that is responsible for the production of energy in the stars in not suitable for use in a terrestrial fusion reactor because the initial step (as shown in the figure earlier) is extremely slow, taking a billion years! It can successfully proceed in the interior of a star only because of the enormous number of protons available in the high-density stellar cores.

For terrestrial use, the most attractive reactions appear to be the deuteron-deuteron (d-d) and the deuteron-triton (d-t) reactions. Deuteron indicates (^2H) hydrogen nucleus with A=2, while triton (^3H) indicated hydrogen nucleus with A=3. The reactions are:

d-d:	$^2H + ^2H \rightarrow ^3He + n$	(Q= 3.27 MeV)
d-d:	$^2H + ^2H \rightarrow ^3H + ^1H$	(Q= 4.03 MeV)
d-t:	$^2H + ^3H \rightarrow ^4He + n$	(Q= 17.59 MeV)

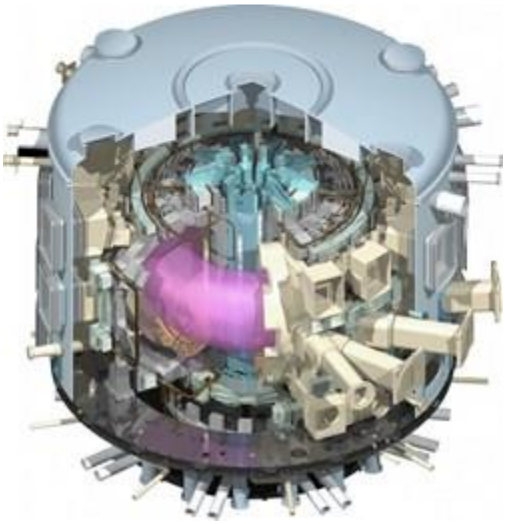
We may note that tritium (atomic ^3H) is radioactive and is not normally found in naturally occurring hydrogen. Basic requirements for successful operation of a thermonuclear reactor include 1) a high particle density, 2) a high plasma temperature; and 3) a long confinement time inside the reactor. The term plasma, incidentally, implies an electrically neutral, highly ionized gas composed of ions, electrons, and neutral particles. It is a phase of matter distinct from solids, liquids, and normal gases.



d-t reaction

To confine the plasma, one technique uses high magnetic fields while the temperature is increased. This is known as *magnetic confinement*. This type of fusion reactor is known as *tokamak*, which stands for a Russian-language acronym for *toroidal magnetic chambe*r. Here, the magnetic field is a modified torus (a doughnut shaped surface). Several large machines of this type have been built and tested. In India, two tokamaks have been built at the Institute of Plasma Research at Gandhinagar, Gujarat, to study the basic processes in a thermonuclear reactor. The planned International Thermonuclear Experimental Reactor (ITER) represents what is hoped to be the final step before practical fusion energy becomes a reality. ITER also means "the way" in Latin. It is expected to generate 500 MW of electricity from deuterium-tritium fusion reactions, and is being built in Southern France, and seven nations are collaborating in this ambitious project including India.

In another technique known as *inertial confinement*, a small amount of fuel is compressed and heated so rapidly that fusion occurs before the fuel can expand and cool. It uses energetic beams to both heat and compress tiny deuterium-tritium pellets by blasting them from all sides. Laser beams have received the most attention for inertial confinement, but electron and proton beams hold promise as well. However, the fact still remains - it is still a long and arduous road ahead to controlled thermonuclear fusion.



Schematic diagram of ITER

Breakeven point

Despite the fact that today fusion science stands at an exciting threshold, we are yet to reach the long sought-after **plasma energy breakeven** point. Incidentally, the breakeven describes the moment when plasma in a fusion device releases at least as much energy as is required to produce it. Till date, plasma energy breakeven has never been achieved. The maximum scientists have been able to achieve so far is 70 percent of input power. For a device to be efficient, it must have higher power output that it consumes to produce it. The promising device ITER, however, is expected to produce more power than it consumes. For 50 MW of input power, it would produce 500 MW of output power. If so, ITER will begin writing a new chapter on fusion energy.

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THE “ITER” STORY

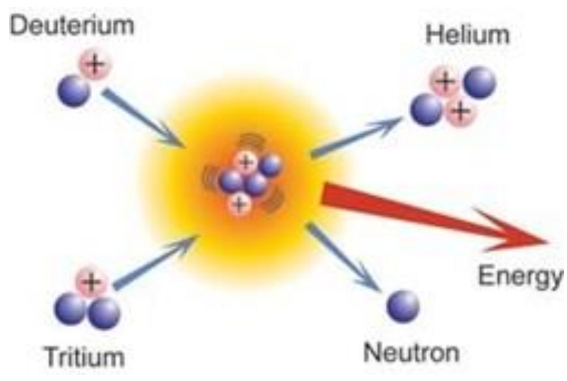
The Birth of ITER

Fossil fuels shaped the civilization in the 19th and 20th centuries. The demand of energy, however, has continued to skyrocket. Global energy consumption is set to triple by the end of the 21st century. Further, the supplies of fossil fuels are depleting and the environmental consequences of their exploitation have been serious. How shall we meet this enormous demand of energy; and that too without adding dangerously to atmospheric greenhouse gases? It is obvious that no single nation can face these challenges alone. It was with these concerns that ITER project was born in1985 after intense deliberations at the Geneva Superpower Summit. Today, Russia, USA, Republic of Korea, China, Japan, India and European Union are collaborating on this ambitious project representing nearly half the world’s population. ITER means "the way" in Latin, and this mammoth project will require unparalleled levels of international scientific collaboration. ITER is being built at Cadarache, near Aix-en-Provence in Southern France. ITER also stands for International Thermonuclear Experimental Reactor.

Indeed, ITER is the culmination of decades of fusion research. Over 200 Tokamaks built in the last several decades the world over have paved the way to the ITER experiment. The smallest was the size of a compact disc, while the largest was as high as a five-storey building! ITER is the result of the knowledge and experience these machines have accumulated. How big the ITER would be? It would be 73 metres tall (60 metres above the ground and 13 metres below), or about twice the size of the largest Tokamak currently operating! A Tokamak, incidentally, is a device using magnetic field to confine plasma in the shape of a torus (donut). Achieving stable plasma equilibrium requires magnetic field lines that move around the torus in a helical shape. ITER is conceived as the necessary experimental step on the road to a demonstration fusion power plant.

A Simple Idea!

In principle, the production of energy in ITER is simple. Just take two heavy isotopes of hydrogen - deuterium and tritium, squeeze them together, and we get a helium atom and a very energetic neutron. This product is slightly lighter than the ingredients we started with, and the tiny loss of mass results in huge release of energy in accordance with Einstein’s mass-energy equivalence equation $E=mc^2$. Once this energy released is harnessed in an efficient way, we have produced controlled nuclear fusion solving the problem of world’s energy needs!



d-t Reaction

A Glitch!

However, there is one glitch! The atomic ingredients of fusion we started with carry positive charge, and like all nuclei, repel each other! In the core of the Sun, the huge gravitational pressure allows fusion reaction to proceed at temperatures of about 15 million °C. In contrast, we need temperatures of the order of 150 million °C to achieve fusion in the machines like ITER. But, no materials on Earth can withstand such high temperatures. Hence, to achieve fusion, ITER will use a device called a Tokamak. A Tokamak holds the reacting plasma away from the furnace's walls with intense magnetic fields.

How much Energy will ITER Generate?

How much energy does ITER aim to generate? It aims to generate 500 megawatts of fusion power. ITER would really be the precursor for a demonstration power plant, called DEMO. In DEMO, fusion power will produce steam, and by way of turbines up to 1000 megawatts of net electrical power. That's equivalent to a power plant that could supply about 2.5 million Indian homes!

Water for fusion!

While deuterium can be extracted from seawater in almost boundless quantities, the worldwide supply of tritium is rather limited - estimated at only 20 kilograms! Hence, fusion power plants will need to produce their own tritium. For this purpose, they will use "tritium breeding modules" made from lithium. Lithium turns into tritium when bombarded by neutrons from the fusion reaction. Further, lithium is a light metal, as abundant as lead. One objective of ITER is to test experimental tritium breeding modules.

Ten times hotter than the core of the Sun

How will ITER handle matter 10 times as hot as the core of the Sun? It will do so by trapping it inside a strong magnetic field. Indeed, magnetic fusion machines of various shapes and arrangements were developed in several countries as early as 1950. But the breakthrough occurred in 1968 in the Soviet Union. Scientists there achieved for the first time remarkably high temperature levels and plasma confinement time – two key criteria for fusion. What was the secret? It was a revolutionary donut-shaped magnetic confinement device called “Tokamak”, developed at the Kurchatov Institute, Moscow. From this time on, Tokamak became the dominant concept in fusion research!

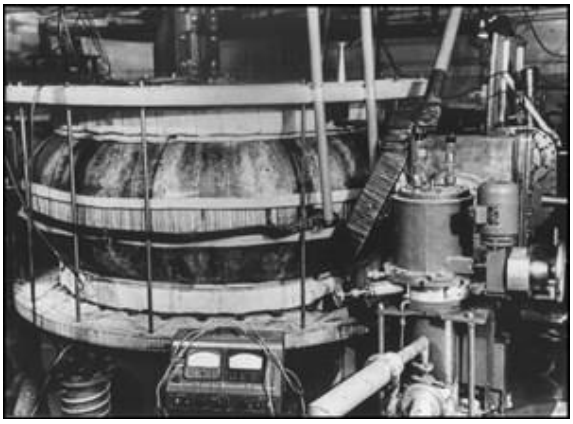
Environmental Impact of ITER

The tremendous heat generated by fusion will be absorbed using 3 million cubic metres of water per year, about a fifth of the total transported by the local river Verdon. Tritium releases are predicted to be 100 times lower than the regulatory limit. What is most important is the fact that the fusion reactions produce no long-lived waste. Low-level radioactive waste will result from the activation of some of the machine's components. All waste materials will be treated, packaged and stored on site.

In all, 39 protected or rare species will benefit from measures on the 180-hectare ITER site. Two areas have been fenced off to protect the Occitan cricket, two species of butterfly, woodlark nesting sites and rare orchids. We may also note that of the 2.5 million cubic metres of earth and rock moved to level the ITER platform, over two-thirds were reused on site.

A Brief History

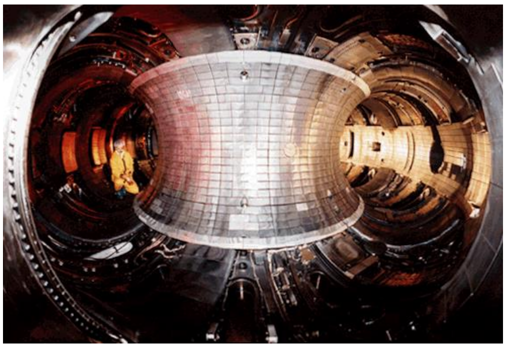
It was some seventy years ago that scientists obtained the first insights into the physics of sunshine - the production of energy in the Sun. Sun and other stars continuously transform hydrogen into helium by fusion; and in the process release colossal amounts of energy. By the mid-1950s, so called fusion machines were operating in the Soviet Union, the United Kingdom, the United States, France, Germany and Japan. Yet, harnessing the energy of the stars proved to be a tough nut to crack.



The world's first Tokamak device: the Russian T1 Tokamak at the Kurchatov Institute in Moscow.

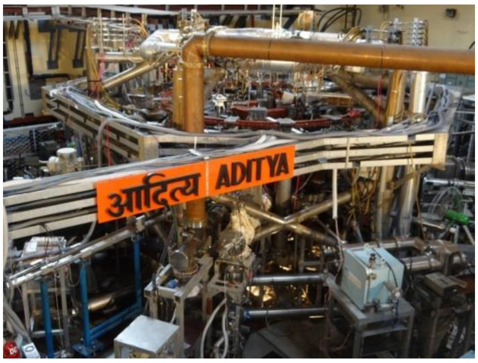
As stated earlier, after pioneering work in the Soviet Union in the late 1950s and 1960s, a donut-shaped device called a ‘Tokamak’ became the dominant concept in fusion research. Ever since, Tokamaks have passed several milestones. Experiments with fusion fuel - a mix of the hydrogen isotopes deuterium and tritium - began in the early 1990s in the Tokamak Fusion Test Reactor (TFTR) in Princeton, USA, and the Joint European Torus (JET) in Culham, UK. *JET marked a key step in international collaboration, and in 1991 achieved the world's first controlled release of fusion power.* While a significant amount of fusion power was produced by JET, and TFTR, exceptionally long-duration fusion was achieved in the Tore Supra Tokamak, a EURATOM-CEA installation located at France's Cadarache nuclear research centre and later in the TRIAM-1M Tokamak in Japan and other fusion machines. We may note that in Japan, JT-60 has achieved the highest values of the three key parameters on which fusion depends – plasma density, temperature and confinement time. Meanwhile, US fusion installations have reached temperatures of several hundred million °C.

Joint European Torus

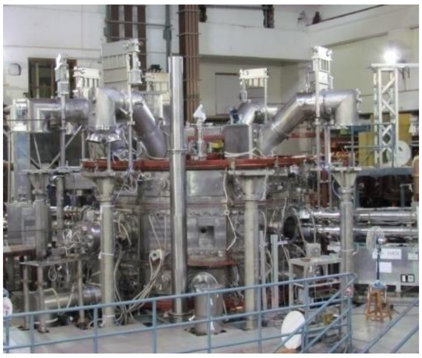


TFTR

In India, two Tokamaks have been built at the Institute of Plasma Research at Gandhinagar, Gujarat, to study the basic processes in a thermonuclear reactor. Aditya is the first indigenously designed and built tokamak of the country, and is a medium sized Tokamak in operation since 1989. SST-1, a steady state super conducting Tokamak, is a second generation machine producing plasma for 1,000 seconds. It started operation in 2010.



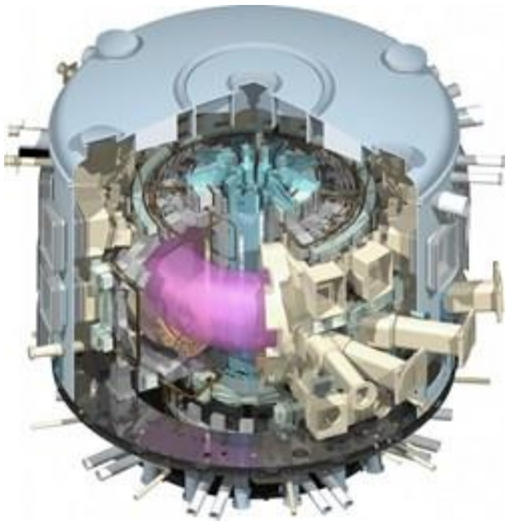
Aditya



SST-1

Goal of ITER: Q ≥ 10

ITER is a large-scale scientific experiment that aims to demonstrate the technological and scientific feasibility of fusion energy. The expression Q ≥ 10 summarises this goal of the experiment. The Q in the formula symbolizes the ratio of fusion power to input power. Q ≥ 10 represents the scientific goal of the ITER project: to deliver ten times the power it consumes.



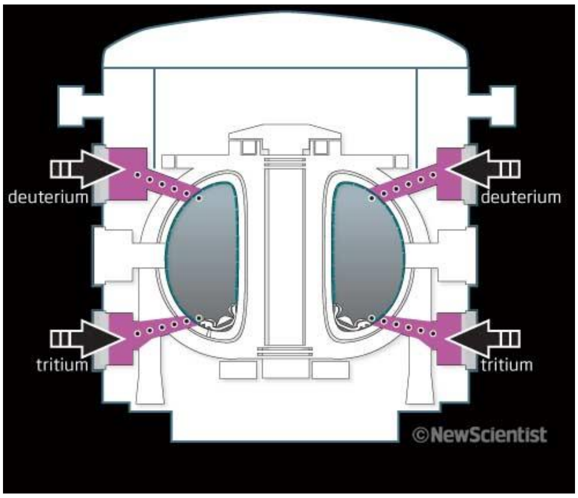
A cut-away view of the ITER Tokamak, revealing the donut-shaped plasma inside of the vacuum vessel

In any energy installation, it is important that the output power produced be more than the input power. When output power equals the input power, “break-even point” is said to have reached. In JET, TFTR and JT-60 scientists have approached the long-sought break-even point, where a device releases as much energy as is required to produce fusion. *ITER's objective is to go much further and release ten times as much energy as it will require for initiating the fusion reaction*. For 50 MW of input power, ITER will generate 500 MW of output power. If all goes well, it would be operational in 2027. Thus, ITER will pave the way for the Demonstration power plant, or DEMO, in the 2030s. As research continues in other fusion installations worldwide, DEMO will put fusion power into the grid by the middle of this century. The last quarter of this century will see the dawn of the Age of Fusion.

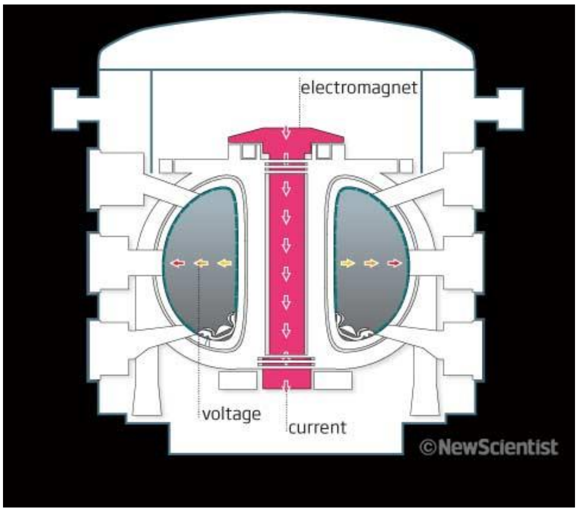
It is interesting to note that over half of the world's population is represented in the ITER Organization. Though it was conceived as long ago as 1985, it was only formally established on 24 October 2007, following an agreement between the People's Republic of China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States of America. Conceptual design work began 20 years ago, in 1988. The final design for ITER was approved in 2001. The construction work on ITER is expected to be completed by around 2020. ITER is expected to work for around two decades.

How ITER Works

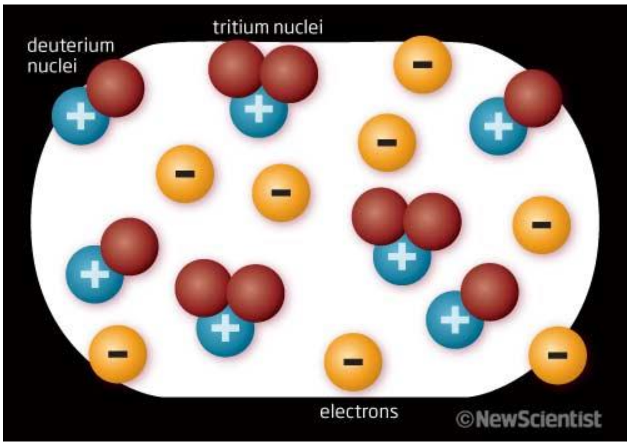
We describe in this section how ITER would work in a step-by-step manner.



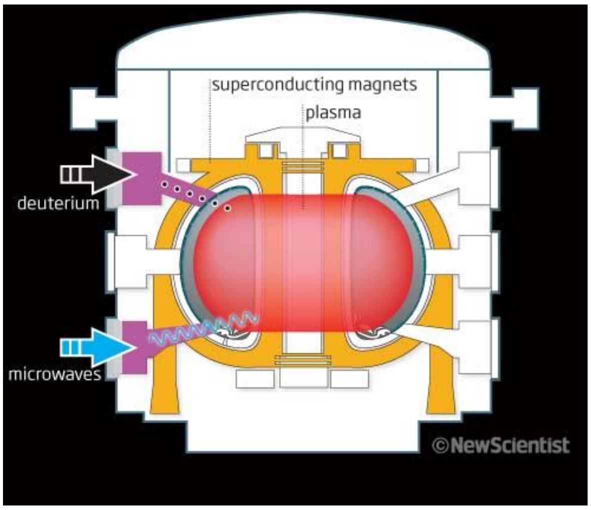
Step 1. Puffs of deuterium and tritium gas are injected into the donut-shaped vacuum vessel, called a Tokamak. The gas weighs less than a postage stamp and fills a volume one-third that of an Olympic swimming pool.



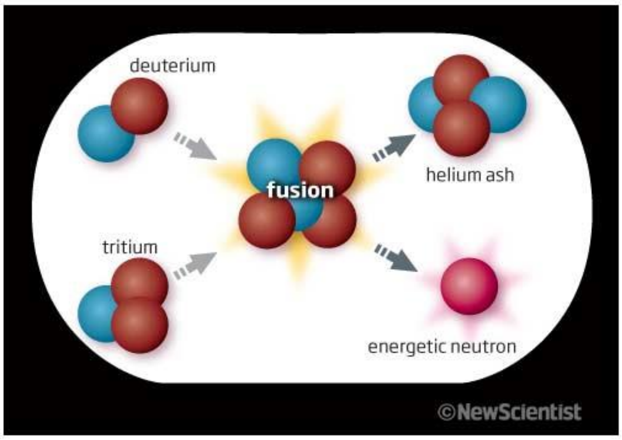
Step 2. Electricity flowing through this electromagnet (central solenoid) produces a voltage across the gas.



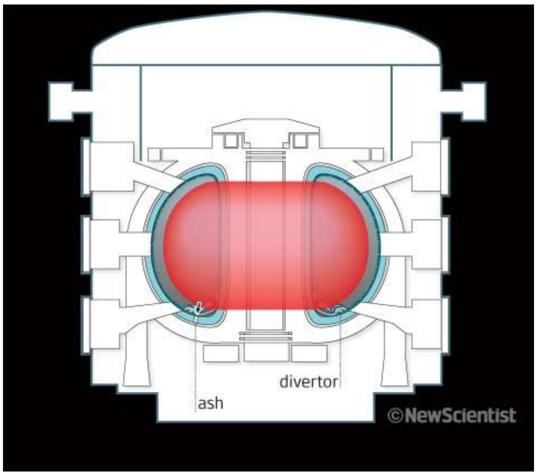
Step 3. Voltage rips electrons from the deuterium and tritium atoms. They turn into charged atoms (ions) within a few microseconds, forming a particle soup called a plasma.



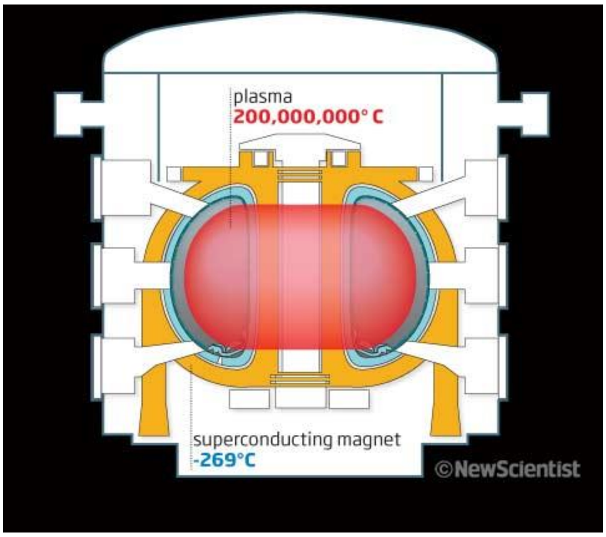
Step 4. Plasma is locked inside the vacuum vessel by magnetic fields that are created by an array of superconducting magnetic coils. The magnetic coils generate a current in the plasma as well as confining it, heating the plasma to 10 million °C. But that's not hot enough for fusion to occur.



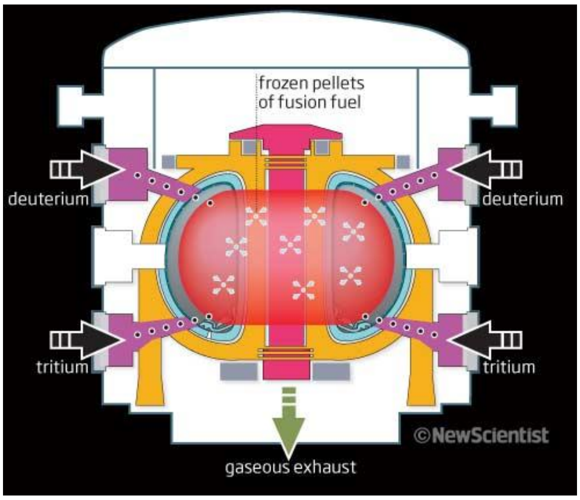
Step 5. To raise the temperature further, scientists fire radio and microwaves into the plasma and high-energy beams of deuterium atoms. The plasma then reaches 100 - 200 million °C, hot enough for the deuterium and tritium nuclei to fuse.



Step 6. Fusion produces high-energy neutrons and helium particles that deposit their energy into the plasma and keep it hot, before becoming "ash". The "ash" is eventually forced out through the divertor.



Step 7. Neutrons and other particles bombard the tiles on the plasma-facing components and heat them. In a future power station this heat will be harnessed to make electricity. Superconducting magnets operate near absolute zero. The distance to the magnets from the heart of the plasma sees the greatest temperature gradient in the universe.



Step 8. The plasma must be continuously refuelled with deuterium and tritium for the process to continue. Unburnt fuel is also recovered from the gaseous exhaust and the reaction is fine-tuned by firing frozen pellets of fusion fuel deep into the plasma.

ITER Facts and Figures
100,000 kilometres of niobium-tin (Nb_3Sn) superconducting strands are necessary for ITER's toroidal field magnets. Stretched end to end, the Nb_3Sn strand produced for ITER would wrap around the Earth at the equator twice.
The ITER machine will weigh 23,000 tons. The ITER Tokamak will be as heavy as three Eiffel Towers.
The ITER Tokamak will be the largest ever built, with a plasma volume of 840 cubic metres. In currently operating tokamaks, the maximum plasma volume is 100 cubic metres.
At the peak of ITER construction in 2018-2019, 5,000 people are expected at ITER.
The heaviest component will weigh nearly 900 tons including the transport vehicle; the largest will be approximately four storeys - or 10.6 metres - high.
Every one of the ITER Tokamak's 18 D-shaped toroidal field coils will weigh 360 tonnes, approximately the weight of a fully loaded Boeing 747-300 airplane. Each toroidal field coil is 14 metres high and 9 metres wide
ITER has been designed to produce 500 MW of output power for 50 MW of input power- or ten times the amount of energy put in. The current record for released fusion power is 16 MW (held by the European JET facility located in Culham, UK).
The temperature at our Sun's surface is 6,000°C, and at its core - 15 million °C. Temperature combines with density in our Sun's core to create the conditions necessary for the fusion reaction to occur. The gravitational forces of our Universe cannot be recreated here on Earth, and much higher temperatures are necessary in the laboratory to compensate. In the ITER Tokamak, temperatures will reach 150 million °C - or ten times the temperature at the core of our Sun.
The main feature of the 180-hectare ITER site is a man-made level platform that was completed in 2009. This 42-hectare platform measures 1 kilometre long by 400 metres wide, and compares in size to 60 soccer fields.
The Tokamak Building will be 60 metres above ground and 13 metres below, and will be the tallest structure on the ITER site.
13 billion Euros is the estimated cost of the ten-year construction phase of the ITER Project, shared by the seven ITER Members. Most of the components will be contributed by the Members themselves, rather than the monetary equivalent.

India’s Contribution to ITER Project

ITER will be built mostly through in-kind contributions from the participant countries in the form of components manufactured by them, delivered and installed at ITER. ITER-India, the Indian Domestic Agency located at Gandhi Nagar, Gujarat, is formed with the responsibility to develop, manufacture, and provide a host of components for ITER. India would contribute equipment worth nearly 500 million US dollars to the ITER experiment, and also participate in subsequent operations and experiments. In particular, India would fabricate a stainless cryostat forming the outer vacuum envelope for ITER that would be of 28 metres diameter and 26 metres tall. The vacuum vessel shields made of 2% boron steel and occupying space between the two walls would also be designed and fabricated in India. India would fabricate eight 2.5 megawatt ion cyclotron heating sources, complete with power systems and controls. Also a diagnostic neutral beam system which will give crucial information about the physics of the burning plasmas in ITER would be fabricated. Finally, India would contribute to cryo-distribution and water cooling subsystems

ITER and Beyond

The objective of the ITER project is to gain the knowledge necessary for the design of the next-stage device: a demonstration fusion power plant. In ITER, scientists would study plasmas under conditions that are expected to be similar to those in a future power plant. What is important is to note that *ITER will be the first fusion experiment to produce net power,* and would be operational in 2027. It will also test key technologies, including heating, control, diagnostics, and remote maintenance. *ITER is not an end in itself*. Rather, it is the bridge toward a first plant that will demonstrate the large-scale production of electrical power and tritium fuel self-sufficiency. This is the next step after ITER: the Demonstration Power Plant, or DEMO for short. A conceptual design for such a machine is likely to be complete by 2017. If all goes well, DEMO will lead fusion into its industrial era, beginning operations in the early 2030s, and putting fusion power into the grid as early as 2040, that is, by the middle of this century.

While ITER is being constructed and DEMO is in its conceptual phase, several fusion installations, with different characteristics and objectives, will be operating around the world to conduct complementary research and development in support of ITER. By the last quarter of this century, if ITER and DEMO are successful, our world will enter the Age of Fusion - an age when mankind covers a significant part of its energy needs with an inexhaustible, environmentally benign, and universally available resource.

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3. www.iter-india.org

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Institute for Plasma Research - An Overview

Introduction

Institute for Plasma Research better known as IPR is a premier organization in India involved in the research of various aspects of plasma science including basic plasma physics, magnetically confined hot plasma leading to fusion reactor and industrial applications of plasma. The main and ultimate goal of plasma science is to build fusion reactors that will provide a solution to the growing need of energy of the world. The conventional sources of energy like coal, petroleum and natural gases are going to be exhausted in few decades. But the way the world is progressing and civilization is increasing, the energy demand is going to increase enormously. In such situation it becomes essential to look for sustainable sources of energy. Fusion energy is one of the answers of ever growing energy need of the world.

IPR is located at the bank of Sabarmati Rivernear Indira Bridge in Bhat village of Gandhinagar district in Gujrat. It is 5 Kms from Ahmedabad airport and around 14 Kms from Ahmedabad railway station. IPR can trace its roots back to early 70's when a coherent and interactive program of theoretical and experimental studies in plasma physics was established at the Physical Research Laboratory (PRL) Ahmedabad. Earlier studies were towards space plasma physics. Later on high power plasma experiments using intense electron beams to form compact toroid and electron rings in toroidal devices started in 1978. This reflected a reorientation to fusion-relevant experiments.

A proposal to initiate studies on magnetically confined high temperature plasmas was submitted to Govt. of India and was accepted in 1982. This resulted into establishment of Plasma Physics Program (PPP) at PRL supported by Dept. of Science & Technology. At the same time the design, engineering and fabrication activities of first Indian tokamak named Aditya was started. In 1984, the activities moved into the today's exiting campus. In 1986, PPP evolved into an autonomous institute; present IPR; under the Department of Science & Technology. With the commissioning of Aditya in 1989, full fledge plasma experiments started.

In order to make fusion reactor, a reality, plasma science laboratories world over were looking for long pulse plasma operations. These long pulse plasma operations were being achieved world over by using super conducting technologies. India joined this endeavor in 1995, with the decision of making Steady State Tokamak - 1(SST-1). Design and engineering activities were subsequently started and the Institute was placed under the control of Dept. of Atomic Energy in 1995. Major new programs for the development of pulsed power, advance diagnostic, computer modeling, RF and neutral beam heating systems came into being at the same time. The use of plasma technologies in industries were reorganized under the Facilitation Center for Industrial Plasma Technologies (FCIPT). Center for Plasma Physics (CPP) Guwahati was associated with IPR in 2003.

In 2005, IPR joined International Thermonuclear Experimental Reactor (ITER). This is a joint project of seven partners/countries which include China, European Union, India, Japan, Russia, South Korea and USA. ITER machine is super conducting tokamak being built at Cadarache in France.

What is Plasma

Plasma is basically an ionised state of gas/matter. This is also called forth state of matter coming after solid, liquid and gas. But in reality it is the first state of matter. Before the exiting of other state of matter, plasma was in existence. Around 99% of the universe is made up of plasma. The examples in daily life are plasma in tube light (fluorescent lamps), sun and space plasma. Any ionised gas may be called plasma but the plasma that is studied in the laboratories called tokamak grade plasma has certain properties. The tokamak grade plasma should have densities, at least of the order of 10^{-10} g/cm^3, temperature of the order of 10 keV where one keV equals roughly 11,000 ^{0}C. There are also few more parameters that are used in defining laboratory or fusion grade parameters and one of them is Debye length. The Debye length is the length travelled by ions of plasma before being colliding with other particles.

Source of Energy at Sun

Since long human is trying to know how the energy is being generated at the Sun. This question is troubling scientists since 19th century when it was proved that energy can neither be created nor destroyed. So what is the source of energy of Sun.

In the early 20th century, with the development of nuclear physics and theory of relativity, scientist could predict that sun and other stars are the hot balloons of gases mainly of hydrogen. They found that the temperature of hot gases; necessary to counter the inward gravitational force of the sun should be around 15 million degree Kelvin. At this pressure hydrogen nuclei have enough energy to fuse together to form helium nucleus. It was also found by that time that helium nucleus has smaller mass than that of two hydrogen nuclei. And the theory of relativity which was established by that time showed that the mass loss had converted into energy by the famous $E = mc^2$ relation. This is that source of energy which is fueling the sun and other stars.

Aditya: India’s First Indigenous Tokamak

Aditya is the first indigenously designed and built tokamak of the country. Tokamaks have a toroidal structure which resembles the tube of a cycle. Aditya is a medium sized tokamak and is in operation since 1989. It has major radius of 75 cm and minor radius of 25 cm. It has the capability of producing 1.2 Tesla of toroidal magnetic field with the help of 20 magnetic field coils placed symmetrically around the torus.

Discharges are produced in the tokamak machine with the Ohmic transformer. The tokamak machine works as a secondary of the transformer. This is a single turn secondary and is a step down transformer. Primary of the transformer is the standard transformer winding. The primary of the transformer works with 2 kV and 20 kA. Gas is fed into the torus machineand then discharged under high electric field. Plasma current flows in the tokamak machine normally called tokamak vessel. This plasma has certain resistance and temperature of the plasma increases due to Ohmic heating I^2R.

Plasma has a property that its resistance decreases with the rise of temperature. This reduces the heating efficiency. Hence above a certain temperature range auxiliary heating is required. This heating is provided in the form of ion cyclotron resonance heating (ICRH) and electron cyclotron resonance heating (ECRH) in which ions and/or electrons resonate with the wave launched into tokamak from outside. A 20 - 40 MHz, 200 KW, ICRH system has been integrated to ADITYA vacuum vessel and successfully operated. A 28 GHz, 200 KW gyrotron based electron cyclotron resonance heating (ECRH) system has also been successfully commissioned on ADITYA tokamak. Both ICRH and ECRH have also been utilized for pre-ionisation experiments.

ADITYA is being regularly operated with the transformer-converter type power system. Plasma discharges of about 100 milli second, 80 - 100 kA of plasma current at 0.8 Tesla of toroidal field are being regularly experimented. Plasma properties like edge plasma fluctuations, turbulence, auxiliary heating, disruptions and its control are being studied during these experiments. Standard diagnostics have been employed to measure these parameters. Figure below gives a view of ADITYA with the auxiliary heating systems attached to it.

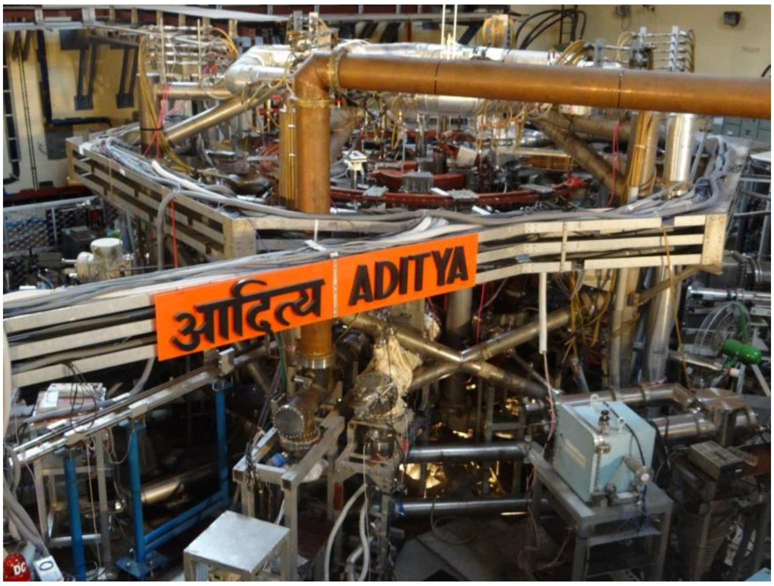

Figure 1: Aditya Tokamak at IPR

Aditya machine is upgraded from time to time depending upon the need of experiment. It has been seen that successful breakdown and startup require compensation of the error magnetic fields in the first few milliseconds. This is accomplished using the four fast feedback coils connected to give a radial magnetic field. Recent measurements of the magnetic fields due to the toroidal field (TR) coils and vertical field (BV) coils also indicate the need for compensation of the error fields. The compensation also helped in improving the operating pressure range, which has the beneficial effect of reducing hard x-rays during the discharge. Plasma current feedback on the loop voltage and vertical field has also been implemented.

Steady State Superconducting Tokamak (SST-1)

SST-1 is a steady state super conducting tokamak. This is second generation of tokamak machine. In the first generation tokamak like Aditya; copper coils are used to generate magnetic fields. Because of these coils which gets heated up due to substantial value of resistance and very high current, long pulse discharges can't be carried out in first generation tokamaks. In second generation tokamaks, superconductors are used for making magnetic field coils. Being super conductors, high magnitude of current can be passed into these coils to generate high magnetic fields for much longer period of time which is the essential requirement of fusion reactors. SST-1 will be used for studying long pulse or steady state operation of plasma. SST-1 is a large aspect ratio tokamak and will produce double null divertor plasma with significant elongation and triangularity.

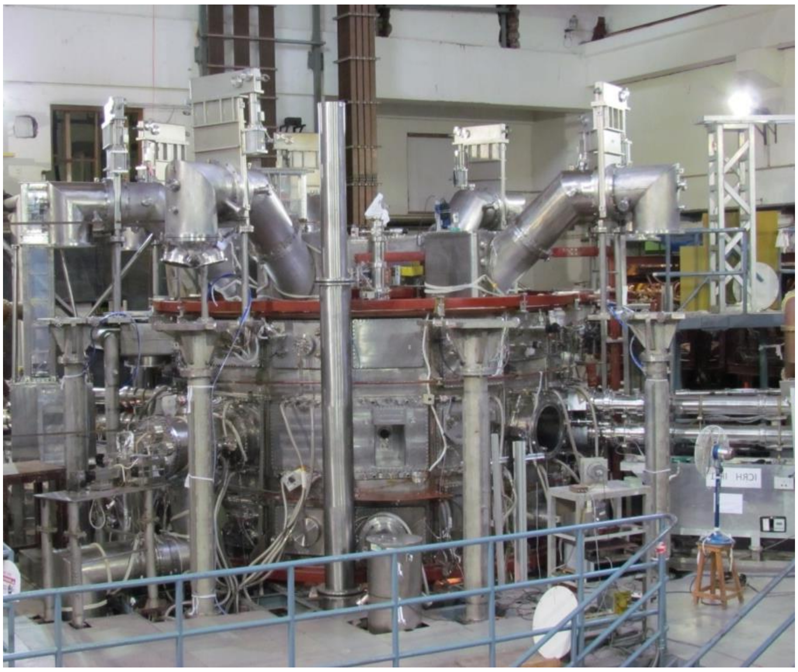

Figure 2: SST-1 Machine at IPR

The prime aim of SST-1 is to produce 1000 second, elongated, double null, divertor plasma. There are many questions in plasma physics which will be addressed in long pulse operations. These include effect of impurities and edge localized modes on energy confinement, stability limits and their dependence on current drive methods, resistive tearing activities in presence of RF fields, disruptions and vertical displacement events (VDE) and thermal instabilities. In steady state operation non-inductive current drive will sustain plasma current. Different aspects of current drive such as different current drive methods and their combinations, current drive efficiency, profile control and bootstrap current, will be studied at SST-1. An efficient divertor is required for the steady state operations with elongated plasma. Various aspects of divertor operation such as steady state heat and particle removal, erosion and particle recycling, radiative diverters and pumped diverters will be studied.

Advance tokamak regimes are of prime interest in fusion research. These regimes are characterized with high B_N and high bootstrap current, and are generally obtained in high (H-mode) and very high (VH-mode) confinement modes in plasma with high triangularity, elongation and large negative shear. Although SST-1 is not optimized for advanced tokamak regimes, we propose to attempt some experiments in this direction within the limitations of the machine.

SST-1 operational parameters are decided by technological and physics aspects. NbTi superconductor at 4.5^0 K is used for the superconducting magnets. Maximum field at the conductor is 5.1 T. Low aspect ratio machines are difficult to design using superconducting coils due to space constraints. Furthermore, higher aspect ratios have the advantages such as high bootstrap current, better confinement etc. Therefore large aspect ratio (~5) is opted in SST-1. Other Tokamaks have observed substantial improvement in confinement (VH mode) and B_N with higher triangularity (δ ~0.4-0.8). Elongation improves the current carrying capacity of the plasma. With elongation in the range of κ~1.6-2.0 improvement in B_N has been observed. Therefore the range of κ and δ has been chosen similar to these ranges. The double null configuration allows for the distribution of power between larger numbers of divertor plates thus reducing the heat load per plate. So the double null configuration has been chosen with a provision to go to single null operations in future.

The machine has a major radius of 1.1 m and minor radius of 0.20 m. The field at the plasma center will be of 3.0 T. The plasma current will be 220 kA. Elongated plasma with elongation in the range of 1.7 to 1.9 and triangularity in the range of 0.4 to 0.7 can be produced. Hydrogen gas will be used and plasma discharge duration will be 1000 s.

Auxiliary current drive will be based mainly on 1.0 MW of Lower Hybrid Current Drive (LHCD) at 3.7 GHz. Auxiliary heating systems include 1 MW of Ion Cyclotron Resonance Heating (ICRH) at 22 MHz to 91 MHz, 0.2 MW of Electron Cyclotron Resonance Heating (ECRH) at 84 GHz and a Neutral Beam Injection (NBI) system with peak power of 0.8 MW (at 80 keV) with variable beam energy in the range of 10-80 keV.

Superconducting (SC) coils for both Toroidal Field (TF) and Poloidal Field (PF) have been deployed in the SST-1 tokamak. An ultrahigh vacuum (UHV) compatible vacuum vessel, placed in the bore of the TF coils, houses the plasma facing components (PFC). A high vacuum cryostat encloses all the SC coils and the vacuum vessel. Liquid Nitrogen (LN_2) cooled thermal shields between the vacuum vessel and SC coils and between cryostat and SC coils reduce the radiation heat load on the SC coils. Normal conductor ohmic transformer system is provided to initiate the plasma and sustain the current for initial period. A pair of vertical field coils is provided for circular plasma equilibrium at the startup stage of the plasma. A set of saddle coils placed inside the vacuum vessel provides fast vertical control of the plasma while PF coils are to be used for shape control. Other subsystems include cryogenic systems at liquid helium (LHe) and LN_2 temperatures and chilled water system for heat removal from various subsystems. A large number of diagnostics for plasma and machine monitoring have deployed along with a distributed data acquisition and control system.

After the refurbishment which started in 2010, SST-1 has start operating. The first plasma discharge has been successfully obtained on June 20th, 2013. With this achievement India has now joined the elite club of countries (Russia, France, Japan, Korea and China) having super conducting tokamaks capable of conducting steady state plasma discharges. Integration of other sub-systems and advanced diagnostics systems are on full swing, along with installations planning for first wall components.

Basic Plasma Physics Experiments

A number of basic plasma physics experiments are operational in IPR. Some of the major experiments are Large Volume Plasma Device (LVPD), Free-Electron Laser (FEL) experiments, non-neutral toroidal plasma studies, dusty plasma experiments, plasma nitriding studies, plasma immersed ion implantation, anode arc studies, radio frequency experiments etc.

In the LVPD experiments, detailed studies are being carried out on excitation and propagation of whistler waves. In the FEL experiment, sheet relativistic electron beam is propagated through a fifty period electromagnet wiggler and radiations in microwave frequency range are observed. Study of dicotron instability and electron cloud behavior in toroidal magnetic field is done in non-neutral plasma experiments. Excitation of dust acoustic waves, formation of coulomb crystal etc. is studied in dusty plasma experiments. Physics of plasma-surface interaction and wave-particle interaction is studied in plasma nitriding and RF experiments respectively.

Facilitation Center for Industrial Plasma Technologies (FCIPT)

Other than fusion reactors, plasma has many other applications which can be used in industry. FCIPT wing of IPR had been raised to exploit those applications of plasma. The main uses of plasma technologies are in material processing and environmental remediation. FCIPT was set up in 1997 to promote the commercial exploitation of plasma technologies through development, incubation, demonstration, manufacturing and transfer. The center has process development and instrumentation laboratories, job shops, material characterization and manufacturing facilities. Advanced plasma process development is realized by validation experiments, scale-up and setting up pilot plants. A number of prototype reactors are available to develop a new idea rapidly from concept to products. Incubation and demonstration of new technologies are carried out in the jobshop to promote the industrial acceptance of plasma based technologies and to generate techno-commercial data relevant to entrepreneurs. The jobshop executes jobwork for surface and material treatment on an industrial scale. The material characterization facility, consisting of advanced instruments is open to users from industry, research establishments and universities. Manufacturing of advanced plasma reactors is another activity crucial to successful commercial transfer of technologies.

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Societal Applications of Plasma :Contribution of IPR

Societal Applications of Plasma at FCIPT, IPR

Facilitation Centre for Industrial Plasma Technologies (FCIPT) links industries with Institute for Plasma Research (IPR), Gandhinagar, India. The knowledge - base in plasma sciences and associated technologies is exploited to generate advanced and non-conventional plasma based technologies for material processing and environmental remediation.

IPR is an autonomous institute under the Department of Atomic Energy (DAE), Govt. of India. It is exclusively devoted to basic research in plasma sciences and development of technological applications. The major thrust is in magnetic confinement fusion and plasma assisted material processing.

FCIPT takes up development of plasma processing technologies from concept to commercialization and promotes awareness of technology through Technology transfer, Newsletters and Direct marketing.

FCIPT was setup in 1997 to promote the commercial exploitation of plasma technologies through development, incubation, demonstration, manufacturing and transfer. The centre has process development and instrumentation laboratories, job shop, material characterization and manufacturing facilities.

FCIPT has a multi-disciplinary team of scientists and engineers with expertise in plasma physics, plasma chemistry, metallurgy, material science, power electronics and instrumentation.

All the above activities under a single roof provide an ideal environment for the centre to offer a complete package of industrial technologies and facilitation services to industries interested in the adoption of indigenous technologies.

Major experiments are as follows:

1) SURFACE ENGINEERING APPLICATIONS
A. Subsurface Modification Glow Discharge Plasma Nitriding

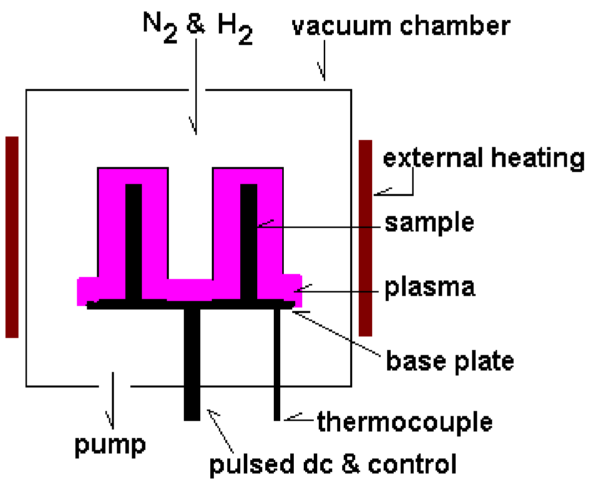
Plasma nitriding is a plasma activated thermo chemical diffusion process that introduces nitrogen into the surface of steel at a temperature range of 400 to 550°C. The nitrogen ions then combines with iron and the alloying elements present in the steel to form their nitrides. This in turns increases the hardness on the surface and improves wear and corrosion resistance.

ADVANTAGES

No Distortion

Retains Base Hardness
Effective Masking
High Repeatability
Control of White Layer
Environmentally Friendly
Hardens stainless steels
No Post Grinding Operation
Prolongs Component Life
Saves Plant Downtime
Reduced Cycle Times

APPLICATIONS
Textile Sector
Automobile Sector
Plastic industries
Tool and Dies industries
Hydropower components

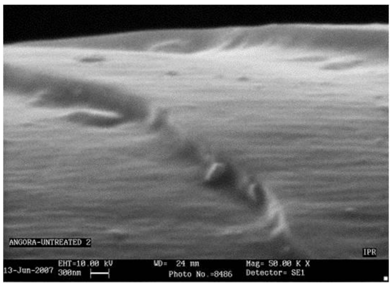


(a) (b)

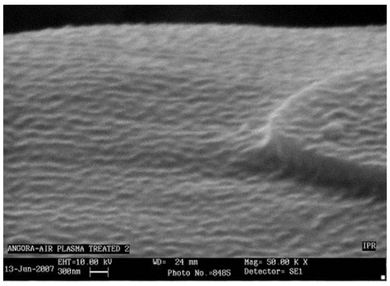
Figure1: (a) Experiemtnal setup for Plasma Nitriding (b) Plasma Glow during Nitriding

B. Surface Activation Plasma etching of wool and other textiles

Angora fiber obtained from Angora rabbit hair is processed at atmospheric plasma to - improves coefficient of friction and cohesion among fibers. Angora fiber is eight times warmer compares to sheep wool and has lesser weight. Raw angora fiber has slippery surface which makes it difficult for spinning. Plasma treatment makes this possible.



SEM image of Untreated Angora fiber



SEM image of Plasma treated Angora fiber

Plasma Treated angora fiber

C. Plasma based coating

Thin film coatings find various applications as hard coatings, antireflective coating, solar coatings etc. Plasma based techniques like magnetron sputtering, PECVD are widely used for thin film deposition.

ADVANTAGES

- ✓ Plasma based coatings are very dense.
- ✓ Have few macroscopic defects.
- ✓ Provides good adhesion
- ✓ Environmentally friendly technique.
- ✓ Ease of sputtering any metal, alloy or compound.
- ✓ Ability to coat heat sensitive Substrates.

Magnetron Sputtering system in FCIPT

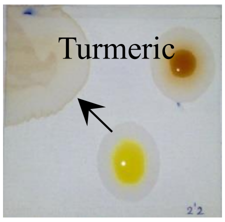
Plasm Aluminizing System

Multiple Magnetron sputtering system for developing solar cell

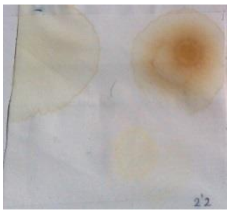
Coating on different types of surfaces

D. Nanomaterial production by Plasma Technology

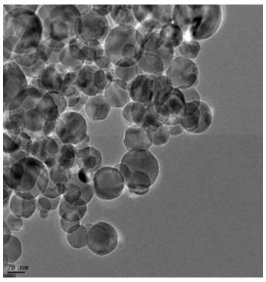
Nanomaterials and nanotechnology has wide ranging applications in varied fields – right from electronics to biomedical systems. Nanosized titanium dioxide particles are used in paints, textiles (self-cleaning) and cosmetic products. Thermal plasma based system has been operational to produce varied nanomaterials with ease in a single step.



Uncoated Fabric



TiO_2 coated fabric



TiO_2 Nanoparticles

Nanomaterial production system

- Large area nanoscale patterning techniques for making nanoparticles arrays for various applications such as improving solar cell efficiency.
- Sensor development for extremely low density molecule detection.
- Nanoscaleplasmonic waveguide for light transport.
- Antibacterial properties in water filters.

E. Plasma Pyrolysis

- ✓ Thermal disintegration of organic waste in absence or controlled oxygen environment
- ✓ Plasma arc as a heat source with core temperature more than 10000 ^{0}C
- ✓ Emissions are within the limit given by US-EPA and CPCB
- ✓ Gases formed in primary reactor used to be at high temperature and also possess high calorific value
- ✓ Energy can be recovered using heat exchangers as well as using combustible gases formed

Plasma Pyrolysis Setup

F. Engineering Applications in Plasma

1) Atmospheric Plasma Jet

- ✓ Developed for the coagulation of blood at the time of accidents.
- ✓ Used for the sterilization of wounds.
- ✓

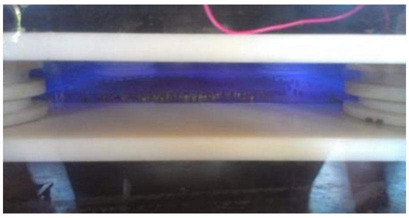
2) Plasma In agricultural Sector

- ✓ Hard seed coat is present which causes delay or no germination.
- ✓ Available methods such as hot water, sulphuric acid, priming are time consuming and are not environmental friendly.
- ✓ This method is a physic-chemical method which has potential to improve

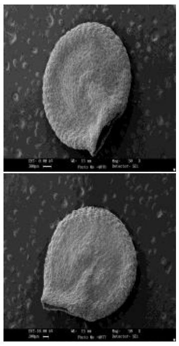
3) Emerging applications in Plasma

- ✓ Removal of pesticides from the vegetables such as capsicum, okra.
- ✓ Plasma Sterilization of surgical equipments

Single Plasma Torch for blood coagulation



Glow discharge plasma system for treatment of capsicum seeds



Untreated and treated Capsicum seed

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Energy from Smashing the Atoms

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Tinkering with atoms

How do we get energy from coal when we burn it in a furnace? When we burn coal, we are tinkering with *atoms* of carbon and oxygen, rearranging their outer electrons in more stable combinations. When we get energy from uranium by consuming it in a nuclear reactor, we are tinkering with its *nucleus*, rearranging its nucleons (protons and neutrons) in more stable combinations. Nucleon is an umbrella term denoting either protons or neutrons, the constituents of nuclei.

We know that the electrons are held in the atoms by the Coulomb force. It takes a few electron volts to remove one of the outer electrons. Incidentally, an electron volt (eV) is a unit of energy equal to the work done by an electron when accelerated through a potential difference of 1 volt. Now, the nucleons are held in nuclei by the strong nuclear force, and it takes several *million* electron volts (MeV) to pull one of them out! Hence we can extract about a million times more energy from a kilogramme of uranium than from a kilogramme of coal. For example, the energy evolved during an exothermic chemical reaction (in which heat energy is liberated) when a carbon atom combines with two oxygen atoms is only about 4 eV. In contrast, when a uranium nucleus $^{235}U_{92}$ (having 92 protons and 143 neutrons) breaks up during a fission process, the energy released is about 200 MeV.

In both atomic and nuclear cases, the appearance of energy is accompanied by the decrease in the rest energy of the fuel. The only difference between consuming uranium and burning coal is that a much larger fraction of the available rest energy is converted to other forms of energy in the case of uranium than in the case of coal - indeed by a factor of million! Table 1 shows how much energy can be extracted from 1 kg of matter through various processes, and how long the extracted energy could operate a 100 Watt light bulb. The last row, the total mutual annihilation of matter and antimatter, is the ultimate in extracting energy from matter, though no one has yet figured out an economical way to produce and store 1 kg of antimatter to use for energy production!

Table 1: Energy from 1 kg of matter

Form of matter	Process	How long could a 100 W light bulb be powered
Water	A 50 metre waterfall	5 s
Coal	Burning	8 h
Enriched UO_2 (3%)	Fission in a reactor	680 y
^{235}U	Complete fission	3×10^4 y
Hot deuterium gas	Complete fusion	3×10^4 y
Matter and antimatter	Complete annihilation	3×10^7 y

Nuclear Fission: The Basic Process

While the proton was discovered in 1919 by Ernest Rutherford, the neutron was discovered by the English physicist James Chadwick in 1932. A few years later, Enrico Fermi and his collaborators in Rome discovered that if various elements are bombarded by neutrons, new radioactive elements are produced. Fermi had predicted that being uncharged, the neutron would be a useful nuclear projectile unlike the proton or the alpha particle since it experiences no electrical repulsion when it approaches a nuclear surface. Since there is no Coulomb barrier for the neutron, a slow neutron can penetrate and interact with even the most massive, highly charged nucleus. It turns out that the most convenient and effective are thermal neutrons, which are neutrons in equilibrium with matter at room temperature (300 K) with a mean kinetic energy of 0.04 eV.

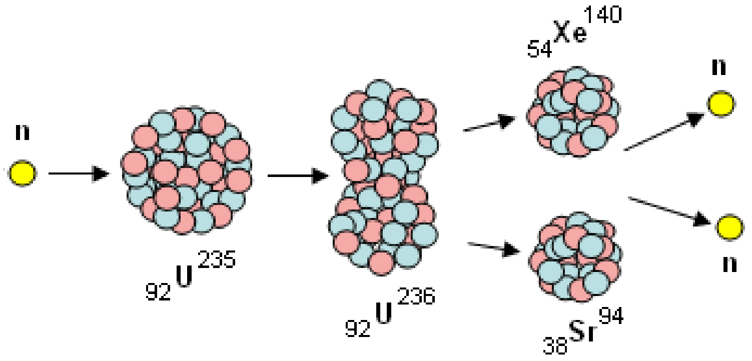
In 1939, Otto Hahn and Fritz Strassmann bombarded uranium with thermal neutrons. After the bombardment, they found that a number of new radioactive elements were produced. One of them was the middle-mass element barium with atomic number Z=56. We may note that Z denotes the number of protons in a nucleus. How could this middle-mass element be produced by bombarding uranium (Z=92) with neutrons? The riddle was soon solved by Lise Meitner *(pronounced Leezet with t silent!)* and her nephew Otto Frisch. They showed that a uranium nucleus, having absorbed a neutron, could split, with the release of energy, into two roughly equal parts, one of which well might be barium. They named this process *nuclear fission*. The fission of ^{235}U by thermal neutrons can be represented by

$$^{235}U + n \rightarrow {}^{236}U^* \rightarrow X + Y + bn$$

where $^{236}U^*$ denotes a compound nucleus. X and Y stand for *fission fragments*, middle-mass nuclei that are usually highly radioactive. The factor b has the average value of 2.47 for fission events of this type, and denotes the number of neutrons released in such events. However, in only about 0.01 % of events the fragments X and Y will have equal mass. We may also note that the most probable mass numbers, occurring in about 7% of events, are the mass numbers A=140 and A=95 (where A, the mass number, is the sum of the protons and the neutrons in the nucleus).

The fission fragments X and Y are called the primary fragments and are excessively neutron rich; and hence unstable. They approach stability by a chain of successive beta decays. Let us consider a specific example:

$$^{235}U + n \rightarrow {}^{236}U^* \rightarrow {}^{140}Xe + {}^{94}Sr + 2n$$



Neutron bombardment of uranium-235 resulting in one possible fission

The fission fragments ^{140}Xe and ^{94}Sr decay through beta decay process (electron emission) until each reaches a stable end product as follows:

$$^{140}Xe \rightarrow {}^{140}Cs \rightarrow {}^{140}Ba \rightarrow {}^{140}La \rightarrow {}^{140}Ce \text{ (stable)}$$
$$^{94}Sr \rightarrow {}^{94}Y \rightarrow {}^{94}Zr \text{ (Stable)}$$

This is only one of the examples of fission of ^{235}U. It does not always split into Xe and Sr but usually into two fragments with nearly equal masses. Barium and krypton is often a result. The number of emitted neutrons is also not always constant but it distributes over one to several. The emitted energy is also not always constant but close to 200 MeV. But, how is it that the splitting of nuclei like ^{235}U produces such high amounts of energy - millions of times more than the chemical reactions?

Energy produced in a fission reaction

How much is the energy produced in the reaction we discussed above? We could write the effective reaction as,

$$^{235}U + n \rightarrow {}^{236}U^* \rightarrow {}^{140}Ce + {}^{94}Zr + 2n + Q$$

where Q is the total disintegration energy produced.

Let us see what we started with and what we got at the end of the reaction. If we replace the fission fragments in the above reaction by their *stable* end products, we see that the *overall transformation* of ^{235}U is:

$$^{235}U \rightarrow {}^{140}Ce + {}^{94}Zr + n.$$

The single neutron comes about because the neutron on the left hand side cancels one of the two neutrons on the right hand side. Now, the atomic masses for ^{235}U and the fission products are as follows:

^{235}U mass = 235.043924 u, ^{140}Ce mass = 139.905433 u
^{94}Zr mass = 93.906315 u, n mass = 1.008665 u

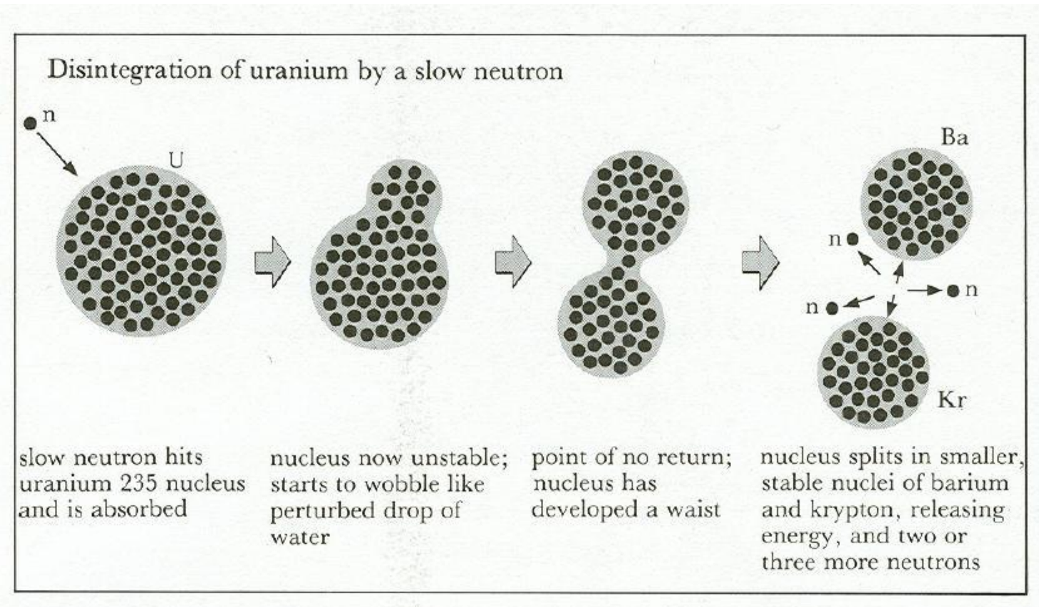
where u stands for atomic mass unit, 1 u= 1.66054 x 10^{-27} kg.

If we add up the masses of fission fragments, we would get for the total mass of the fission fragments as 234.820413 u. Thus, the mass difference for this reaction would be, Δm = 235.043924 u – 234.820413 u = 0.223511 u.

Apparently the equivalent of Δm = 0.223511 u of mass has disappeared! Where did it go? According to Einstein's mass - energy equivalence relation $E = mc^2$, (where c is the speed of light), the mass that disappeared has transformed into energy Q, the disintegration energy. Thus, Q = (0.223511 u) x c^2 = 208.2 MeV. Almost 80% of this disintegration energy Q is in the form of the kinetic energy of the two fragments, and the remaining goes to the neutron and the radioactive decay products. If the fission event takes place in a bulk solid, most of the disintegration energy appears as an increase in the internal energy of the solid, which shows up in a corresponding increase in its temperature. Five per cent or so of the disintegration energy , however, is associated with the neutrinos that are emitted during the beta decay of the primary fission fragments. This energy is carried out of the system and does not contribute to the increase in its internal energy.

How the fission proceeds

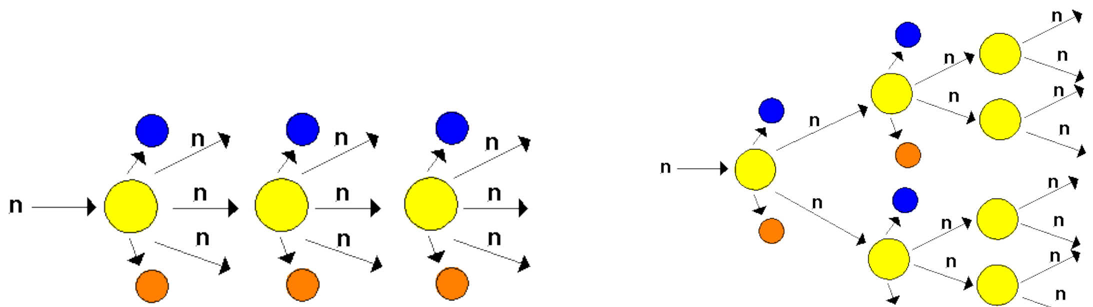
When a heavy nucleus like ^{235}U absorbs a thermal neutron, it forms a $^{236}U^*$ nucleus with excess energy; and it starts oscillating violently. This oscillating motion makes it behave like an energetically oscillating charged liquid drop. It then sooner or later develops a short *neck* and then begins to separate into charged *globs* or *clumps*. If the conditions are right, the electrostatic repulsion between these two globs will force them apart, breaking the neck. The two fragments then fly apart, still carrying some excitation energy, prompting neutrons to boil off. *The fission has occurred!*



We may note that ^{235}U and ^{239}Pu (plutonium with atomic number Z=94) nuclei can fission if bombarded with thermal neutrons (with energy 0.04 eV), while ^{238}U does not. We say that ^{235}U and ^{239}Pu have much larger *cross sections* for the fission process to occur, while it is much smaller for ^{238}U. Incidentally, the cross section is a measure of the probability for a nuclear reaction to occur; and is measured in units of *barn* (1barn = 10^{-28} m^2). We may note that ^{238}U can be made to fission if it absorbs a substantially energetic, rather than a thermal, neutron. The neutron absorbed by ^{238}U must have energy of at least 1.3 MeV for the fission process to occur with reasonable probability. At this energy, the cross section is large enough for fission to occur for ^{238}U.

The Chain Reaction

Soon after nuclear fission was discovered, it was realized that because the fission leads to other neutrons being given off which can cause further fissions, a self-sustaining sequence of fissions should be possible. This self-sustaining sequence was called the *chain reaction*. What could be the condition for a chain reaction to proceed? At least one neutron produced during each fission must cause one more fission, on the average. Certainly, if too few neutrons cause fissions, the chain reaction will slow down and eventually stop. If one neutron per fission causes another fission, energy will be released at a constant rate. Such a reaction is called a *self-sustaining* chain reaction. This is what happens in a *nuclear reactor*. However, if the frequency of fissions increases, the reaction becomes uncontrolled, and the energy release would be so rapid that an explosion will occur, which is the case of an *atomic bomb*. We may note that these situations are called *subcritical*, *critical* and *supercritical*.



Controlled nuclear chain reaction (only 1 neutron from each fission goes on to produce another fission)

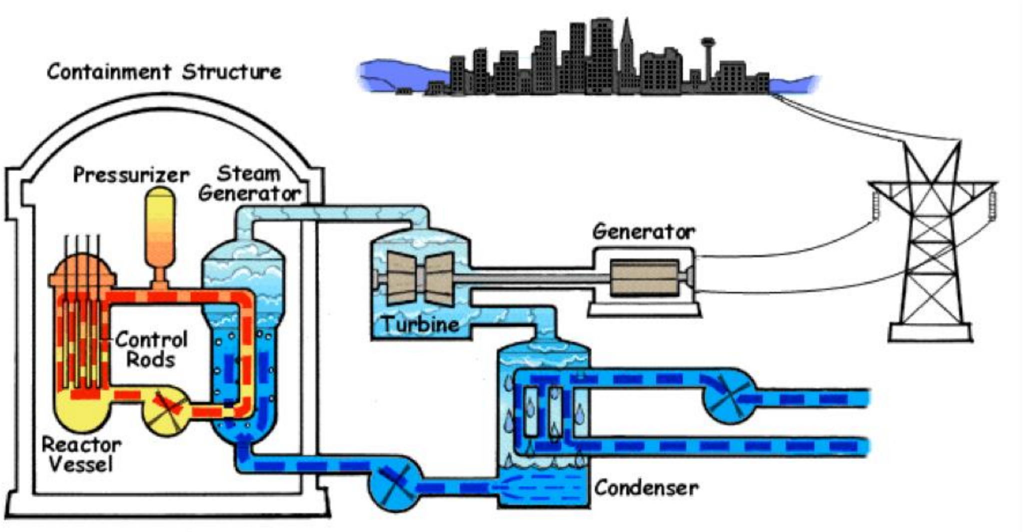
Uncontrolled chain reaction

If two neutrons from each fission in an atomic bomb induce further fissions in 10^{-8} s, a chain reaction starting with a single fission will give off 2×10^{13} Joules of energy in less than 10^{-6} s. This would be equivalent to energy released when 0.25 kg of ^{235}U undergoes fission or 4.75 kilotonnes of TNT (trinitrotoluene, an explosive) explodes. The Little Boy atomic bomb dropped on Hiroshima on 06 August 1945 exploded with energy of about 15 kilotonnes of TNT, and the Fat Man atomic bomb dropped on Nagasaki on 09 August 1945 exploded with energy of about 20 kilotonnes of TNT. The first nuclear explosion test *Smiling Buddha* by India on 18 May 1974 had a yield of 12 kilotonnes equivalent of TNT. The nuclear weapons currently in the arsenal of the United States range in yield from 0.3 kilotonne to 1.2 megatonne equivalent of TNT.

Nuclear Reactor

A nuclear reactor is a very efficient source of energy. Fission of 1 gram of ^{235}U per day produces energy at a rate of about 1 MW. To produce the same amount of energy, however, 2.6 tonnes of coal per day must be burned in a conventional power plant. The energy given off in a reactor is in the form of heat, which is removed by a liquid or a gas coolant. The hot coolant is then used to boil water, and the resulting steam is fed to a turbine that can power an electric generator. It could even power a ship or a submarine.

Each fission in ^{235}U releases an average of 2.5 neutrons, and no more than 1.5 neutrons are lost per fission. Hence at least one neutron is available for fission of another ^{235}U nucleus and thus a chain reaction can be sustained. Natural uranium contains only 0.7 per cent of the fissionable isotope ^{235}U. Although the more abundant ^{238}U can readily absorb fast neutrons produced in the fission of ^{235}U, it does not undergo fission. As mentioned earlier, ^{238}U has a much smaller cross section for the capture of slow neutrons, whereas it is quite large for ^{235}U. Hence, slowing down the fast neutrons that are liberated in the fission prevents absorption by ^{238}U and promotes further fissions of ^{235}U. To slow down the fission neutrons, the uranium reactor is mixed with a moderator. A moderator absorbs the energy of fast neutrons in collisions without any capture of neutrons, and thus slows them down. This process is more efficient if the moderator has a mass comparable ot that of neutrons. This is why the majority of today's commercial reactors use light water both as moderator and coolant. Each molecule of water has two hydrogen atoms whose proton nuclei have masses almost identical with that of the neutron, thus making light water an efficient moderator.



However, protons (^1H) tend to capture neutrons to form deuterons (^2H). Light-water reactors therefore cannot use natural uranium for fuel. They rather use enriched uranium, in which ^{235}U component is increased to about 3 per cent. Thus, higher availability of ^{235}U helps sustain the chain reaction. A water-moderated reactor uses ^{235}U as fuel, and consists of uranium oxide (UO_2) pellets which are sealed in long, thin tubes. To adjust the rate of the chain reaction, control rods of cadmium or boron are used that can easily absorb slow neutrons. These control rods can be slid in and out of the reactor core and adjust the rate of the fission reaction. In the most common design of a reactor, the water that circulates around the fuel in the core is kept at a high pressure, say, about 155 atmospheres. This prevents boiling of the water. The water, acting as a moderator and a coolant,is passed through a heat exchanger to produce steam that drives the turbine. The reactor fuel must be replaced every few years as its ^{235}U content is used up.

Breeder Reactors

Some non-fissionable nuclides (nuclei with specific number of protons and neutrons) can become fissionable by absorbing neutrons. For example, consider ^{238}U. It becomes ^{239}U when it absorbs a neutron. This uranium isotope quickly decays (in about 23 minutes) through electron emission (beta decay) to $^{239}Np_{93}$, an isotope of the element neptunium, which is also beta-active with a half life of 2.3 days, and yields $^{239}Pu_{94}$, an isotope of plutonium, which is long-lived with a half-life of 24,000 years. We may note that both neptunium and plutonium are *transuranic* elements, and not found on the Earth. We do not find them on Earth because even if they were present when the Earth came into being 4.5 billion years ago, they would not survive since their half lives are too short. We may note in passing that till date transuranic elements up to atomic number (Z=118) have been produced in the laboratory, all of which are highly radioactive and short-lived.

Now, the plutonium isotope ^{239}Pu is fissionable, and can be used as a reactor fuel and for weapons. This is how a *breeder reactor* converts otherwise useless ^{238}U, which is 140 times more abundant than the fissionable ^{235}U. A breeder reactor is especially designed to produce more plutonium ^{239}Pu than the ^{235}U it consumes. The widespread use of breeder reactors would mean that the known reserves of uranium could fuel reactors for many centuries! However, since ^{239}Pu could be, and *is* used for manufacture of nuclear bombs, the production of ^{239}Pu in a breeder reactor also could complicate the control of nuclear weapons in the world. In any case, breeder reactors have proved to be extremely expensive and have severe operating problems.

Like ^{238}U, the thorium nuclide $^{232}Th_{90}$ also is a *fertile* nuclide. $^{232}Th_{90}$ can be transformed into another nuclide which is fissile and hence could be used as fuel in a nuclear reactor. After absorbing a neutron, and undergoing two beta decays, $^{232}Th_{90}$ transforms to ^{233}U, *which is fissionable*. Transformations of ^{238}U to ^{239}Pu and ^{232}Th to ^{233}U are the basis of a breeder reactor, which produce more fuel than is used up in the form of ^{235}U! India is looking into this possibility intently, since our uranium deposits are meagre, though thorium deposits are sizeable.

Energy from nuclear fusion

Energy can also be released if two light nuclei are combined to form a nucleus of somewhat larger mass number. The heavier nucleus thus formed has a mass *less* than the light nuclei taken together before the reaction. This mass defect (difference) appears as energy in accordance with the mass-energy relation of Einstein. This process is called *nuclear fusion*. This process, however, is hindered by the mutual Coulomb repulsion that tends to prevent two such positively charged particles from coming within the range of each other’s nuclear forces and “fusing”. It turns out that for two deuterons (^{2}H), the energy required for each particle to penetrate this Coulomb barrier is about 200 keV. How to attain such high energy to achieve fusion? At room temperature, the mean thermal energy of a particle is only about 0.04 eV! The best way to obtain fusion in bulk matter would be to raise the temperature of the material, so that the particles have sufficient energy to overcome the Coulomb repulsion due to their thermal motions alone. This process is called *thermonuclear fusion*.

At room temperature, the mean thermal kinetic energy of a particle being quite small, we do not expect the fusion reaction to take place. Even at the centre of the Sun with a temperature of about 1.5×10^7 K, the mean thermal kinetic energy is only about 1.9 keV, which is again far too less than 200 keV barrier. And yet we know that thermonuclear fusion not only occurs in the solar interior, but is its central and dominant feature. How does the nuclear fusion reaction proceed in the Sun's interior, then? Although 1.9 keV is the *mean* thermal kinetic energy; particles with much greater energies than this mean value are also present, though in small numbers. Further, it is also possible for the particles with kinetic energies below the barrier energy to "tunnel" through the barrier to a significant level - a purely quantum mechanical phenomenon! It is through these processes that fusion reaction takes place in the interior of the Sun.

We already have many reactors that produce energy through nuclear fission. But, could we build a reactor to produce energy through controlled thermonuclear fusion? We have large amounts of hydrogen stored in the seas and oceans in the form of water, and hence a vast potential for producing energy through fusion. True, the prospects do look attractive! Fusion reactions have indeed taken place on Earth only since October 1952, when the first fusion (or hydrogen) bomb was exploded. The high temperatures needed to initiate the thermonuclear reaction in this case were provided by a fission bomb used as a trigger. However, a sustained and a controllable thermonuclear power source, a fusion reactor, has proved to be much more difficult to achieve. The goal, however, is being vigorously pursued as many perceive it as the ultimate power source of the future, at least as far as the generation of electricity is concerned.

Nuclear Energy: It's not about power and weapons alone

Nuclear energy does not imply nuclear reactors and nuclear weapons alone! It is safe, environmental-friendly, and has innumerable applications in fields as diverse as health and medicine, industry, hydrology, food preservation, and agriculture. In India in particular, we may note that in the field of nuclear agriculture, the mutant groundnut seed developed at the Bhabha Atomic Research Centre (BARC), contribute to nearly 25 per cent of total ground-nut cultivation in the country. Similarly, the BARC developed mutant seeds of black gram (urad) contribute to 22 per cent of the national cultivation. In the state of Maharashtra, this percentage is as high as 95 per cent. There is no gainsaying the fact that so far as the future energy needs and economic development are concerned, nuclear energy is bound to prove extremely beneficial to our country in the decades to come.

Surely, we have come a long way since the discovery of the nucleus by Ernest Rutherford in 1911 and the discovery of the atomic structure by Niels Bohr in 1913!

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Established in 1986, the Institute for Plasma Research (IPR) is an autonomous institute under the Department of Atomic Energy, Government of India with a mandate to pursue R&D in Plasma Science and technology, with an emphasis on magnetically confined plasmas (Tokomaks), to promote industrial and societal applications of plasma based technologies, and to stimulate plasma research in India. IPR has indigenously built and commissioned India's first Tokomak "Aditya" and an advanced tokomak machine "Steady State Tokomak, SST-1". India is one of the partner nations in the ambitious international project called International Thermonuclear Experimental Reactor (ITER), a step towards future harnessing of power from nuclear fusion process.

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