

FUSION CONCEPTS

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"Every time you look up at the sky, every one of those points of light is a reminder that fusion power is extractable from hydrogen and other light elements, and it is an everyday reality throughout the Milky Way Galaxy."
Carl Sagan, Spitzer Lecture, October 1991

"Heavier-than-air flying machines are impossible."
Lord Kelvin, President of the Royal Society, 1895.

INTRODUCTION

Fusion energy is considered as a clean source of energy with a basic fuel that is abundant, cheap, and available to all of humanity. It is now being realized in the Cosmos in stellar systems (Fig. 1) and on Earth in the form of thermonuclear or hydrogen weapons. However, a controlled fusion reaction releasing energy on Earth in a controlled manner remains unfulfilled until sometime in the future.

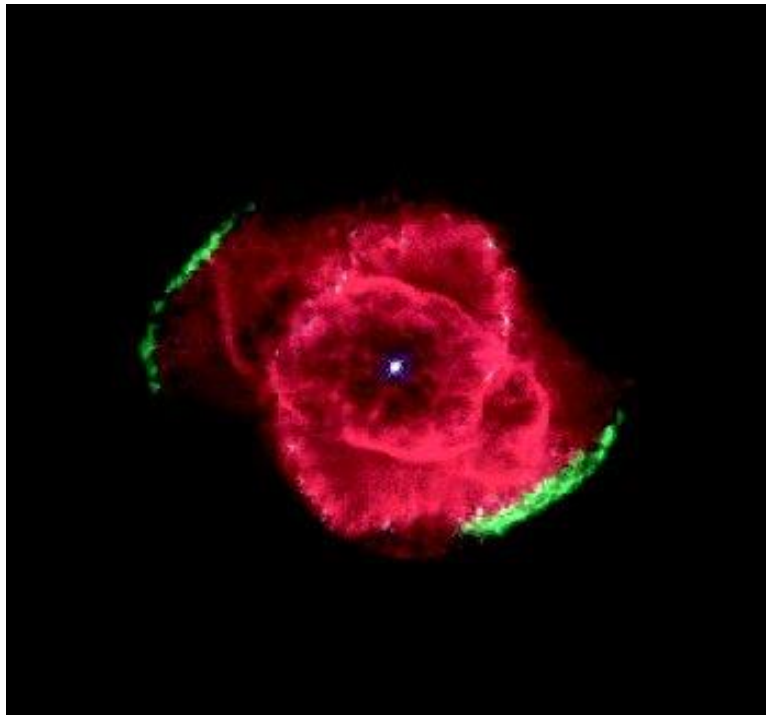


Figure 1. Cat eye nebula, NGC6543. Source: NASA.

Moving away from a carbon economy in the future to a hydrogen economy, because of the concerns about fossil fuels depletion and pollution and global warming, is an incentive for moving to fusion energy production. This opens the prospect for a doubly hydrogenated energy economy. First hydrogen isotopes such as deuterium can be used to produce fusion energy.

Second the energy generated from these isotopes can be used through high temperature electrolysis to decompose water into hydrogen and oxygen. Hydrogen becomes a carrier to the fusion energy in addition to other sources of energy such as solar, wind and biological sources.

Hydrogen can be used as a non-polluting transportation fuel, since it returns water back to the atmosphere upon combustion. As an extra bonus, if hydrogen is delivered through pipelines to remote arid locations, this would provide these regions with both electricity and fresh water for agriculture, alleviating the population growth pressures, and enhancing the standard of living of the new world populations.

Fusion fuels are cheap and uniformly distributed on Earth. Seawater contains deuterium D in practically inexhaustible quantities (Table 1). Tritium, a radioactive isotope of hydrogen with a short half life of 12.33 years, hardly occurs in nature. It can, however, be produced in a power plant from lithium, which is likewise abundantly available.

Table 1. Natural abundance atomic ratios and mass ratios of some fusion relevant isotopes.

Deuterium to hydrogen atomic ratio	$\frac{n_D}{n_H} = 1.5 \times 10^{-4}$
Helium ³ to helium ⁴ atomic ratio	$\frac{n_{He^3}}{n_{He^4}} = 1.3 \times 10^{-6}$
Lithium ⁶ to lithium ⁷ atomic ratio	$\frac{n_{Li^6}}{n_{Li^7}} = 8.0 \times 10^{-2}$
Electron to deuteron mass ratio	$\frac{m_e}{m_D} = 2.72 \times 10^{-4} = 1/3670$
Electron to triton mass ratio	$\frac{m_e}{m_T} = 1.82 \times 10^{-4} = 1/5496$

Since a fusion power plant will have ecologically favorable properties, fusion could make an enduring contribution to the future energy supply. The following applications are foreseen for fusion energy:

1. Electrical power production.
2. Fresh water desalination.
3. Hydrogen production.
4. Deactivation of fission reactors waste.
5. Production of fissile fuel for fission reactors.
6. Space rocket propulsion.

HISTORICAL DEVELOPMENT

Serious research towards obtaining useful power by controlled thermonuclear reactions began during the Second World War. Rumors exist about conventional explosives being unsuccessfully used by German scientists in an attempt at fusing the nuclei of deuterium.

Thermonuclear reactions had been looked for in gas discharges and exploding wires loaded with deuterium before the war, but none had been detected. Rutherford remarked in 1933 that: "Anyone who looks for a source of power in the transformation of the atom is talking moonshine." However Hans Bethe described the fusion reactions in the stars in 1938, for which he received the Nobel Prize.

At the end of the war fusion physics were studied in connection with the possibility of thermonuclear weapons in the Super project. This activity did not lead to a coherent theoretical or experimental program and the team at Los Alamos dispersed into other fields.

At Liverpool University in 1949 Reynolds and Craggs searched for neutrons in sparks in deuterium gas at atmospheric pressure, but none was found. In 1946 work was initiated by G.P. Thomson at the Imperial College in London, who had worked with his father J. J. Thomson on ring discharges in gases during the 1920s and 1930s and by Peter Thonemann, an Australian who arrived in Oxford from Sydney in 1946. Both by 1947 investigated toroidal systems, with the aim of plasma confinement using the pinch effect. Thomson had already worked out a complete installation, described in a secret patent dated 1946. Thonemann with more limited means at his disposal set off with a sequence of experiments to look at the problems one at a time. Both were soon joined by additional workers, and in a few years the Harwell laboratory in the UK had assumed financial responsibility for the work, kept secret because of one of its proposed usages as a neutron source for breeding fissile fuels.

In the USA, Lyman Spitzer an astrophysicist at Princeton had proposed and built a figure of eight Stellarator and studied the requirements for a net power producing system.

At Los Alamos, James Tuck started the Perhapstron, an inductively driven toroidal system. By 1952, the American program was well established with other ideas, including mirrors, emerging elsewhere.

The Russian program was also developing. Sakharov and Tamm had suggested magnetic insulation in 1950, and an experimental program was well under way soon after. Knowledge of the effort became known in a lecture by Kurchatov at Harwell in 1956.

By 1958 the subject had gathered momentum; it was no longer secret and made a major impact at the 1958 Atoms for Peace Conference in Geneva. Despite the collapse of over-inflated hopes when the Zeta experiment neutrons were found not to be thermonuclear, hopes ran high and many alternative concepts were considered.

The following decade saw a more sober realization of the intractability of the containment problem, and hopes collapsed. These were revived by the success of the Soviet Tokamak concept, and the whole subject received a boost during the 1973 energy crisis. Large scale Tokamak and mirror machines were planned and built in the years that followed.

The inertial confinement concept emerged from the American weapons stewardship program. A succession of miniature fusion pellets, millimeters in diameter, would be ignited by immersing them in an intense flash of laser light, from large laser installations. Irradiation by intense bursts of light or heavy ions promised to be more attractive than lasers, provided that the very challenging demands presented to the accelerator community could be met. Inertial confinement also poses extreme and unusual demands on the designers of the reactor system.

At the end of the 1970s some of the urgency of the program had subsided, but the need for a steady development program was appreciated. This would require very large installations to explore conditions closer to those expected to occur in a net power producing reactor. During the following decades large Tokamak experiments were built in the USA, Japan and most notably in Europe, where JET, the Joint European Torus first came into operation in 1983.

Much has been learned by building and operating these machines, particularly regarding the heating by radio frequency and by injected beams, and finding an optimum configuration for the magnetic field.

The next stage involved a design study, involving full participation of the European Community, the USA, Japan and Russia on a large Tokamak, the International Thermonuclear Experimental Reactor, ITER intended to demonstrate all the features, physical and technical, required for a commercial reactor.

Inertial confinement studies continues by enthusiastic groups in Europe, the USA and Japan, but very large extrapolations from present technology of the driver and reactor systems are still required before the technical feasibility of a reactor can be established.

ADVANTAGES OF FUSION ENERGY

As a source of energy, fusion would offer many advantages:

1. Abundant fuel supply. The major fuel, deuterium D, may be readily extracted from ordinary water, which is available to all nations. The surface waters of the earth contain more than 10^{12} metric tonnes of deuterium, an essentially inexhaustible supply. The tritium required would be produced from lithium, which is available from land deposits or from sea water which contains thousands of years' supply. The world-wide availability of these materials would thus eliminate international tensions caused by the imbalance in the fossil fuel supplies.

2. Non critical design. In comparison to fission power plants, no risk of a nuclear criticality accident exists. The amounts of deuterium and tritium in the fusion reaction zone will be so small that a large uncontrolled release of energy would be impossible. In the event of a malfunction, the plasma would strike the walls of its containment vessel and cool itself out.

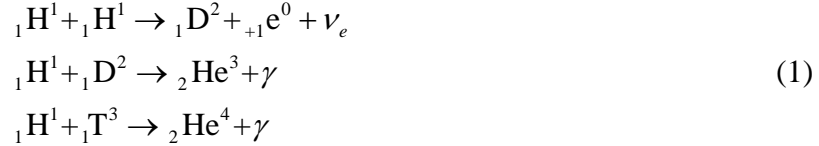
3. No air pollution. Since no fossil fuels are used, there will be no release of chemical combustion products because they will not be produced.

4. No high level nuclear waste. Similarly, there will be no fission products nor transuranics formed to present a handling and disposal problem. Radioactivity will be produced by neutrons activating the reactor structure, but careful materials selection is expected to minimize the handling and ultimate disposal of the activated materials.

5. No generation of weapons material. Another significant advantage is that the materials and by-products of fusion are not suitable for use in the production of nuclear weapons.

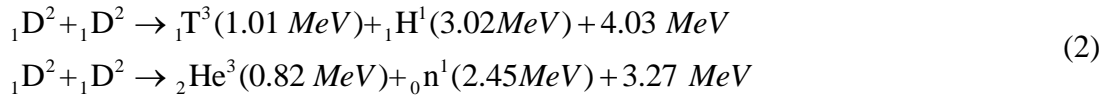
FUSION REACTIONS

In fusion, the reacting nuclei must overcome the Coulomb barrier repulsion between them. Since the Coulomb energy barrier increases in height with increasing atomic number, fusion reactions with low Z number nuclei can occur easier than with heavier nuclei. The three possible reactions with hydrogen H nuclei:



where ν_e is an electron neutrino, are known to have reaction cross sections too small to permit a net gain of energy at the technologically attainable temperatures.

Thus one has to go to the next most abundant isotope, deuterium with its DD reaction possessing a neutron and a proton branches:

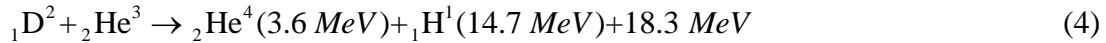


For first generation fusion reactors, the DT reaction is considered as the easiest to achieve, since it requires the lower plasma temperature to be achieved (Fig. 2):

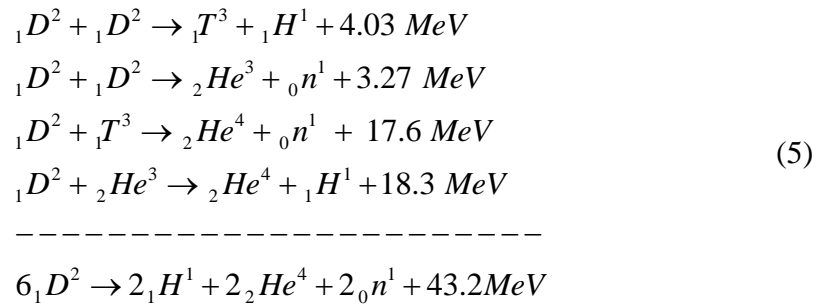


The 17.59 MeV energy release from this reaction is equivalent to 94,000 [kW.hr/gm] of DT fuel.

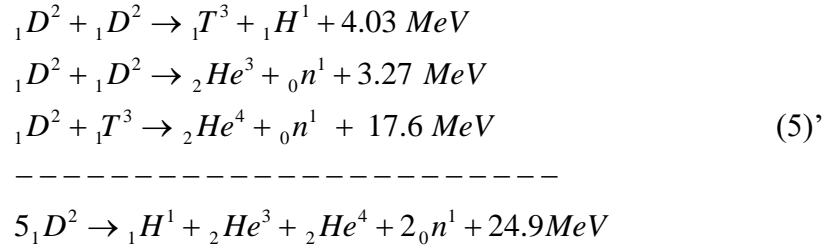
The He^3 produced in the neutron branch of the DD reaction can react with deuterium in a reaction producing charged particles and no neutrons as:



In a fusion reactor using deuterium, the four last reactions should be expected to occur simultaneously in what is designated as the Catalyzed DD reaction, where six deuterons are fused with a release of energy of 43.2 MeV, or $43.2/6 = 7.2$ MeV per deuteron: Tritium and He^3 act as catalysts in the overall reaction.



For kinetic reactions temperatures below 50 keV the DHe^3 reaction is not significant and the energy release would be $43.2 - 18.3 = 24.9$ with each of the five deuterons contributing an energy release of $24.9/5 = 4.98$ MeV.



Whereas deuterium (D) occurs in the water in the oceans and can be extracted through electrolysis or distillation, tritium (T) does not appreciably occur in nature since it is radioactive with a half life of 12.34 years. Tritium has to be produced or bred from the isotopes of lithium through interaction of the neutrons produced in the fusion reactions with lithium surrounding the fusion reaction in the form of a blanket. Lithium or its compounds could also be used as a coolant absorbing the 14.1 MeV of energy carried out by the fusion neutrons.

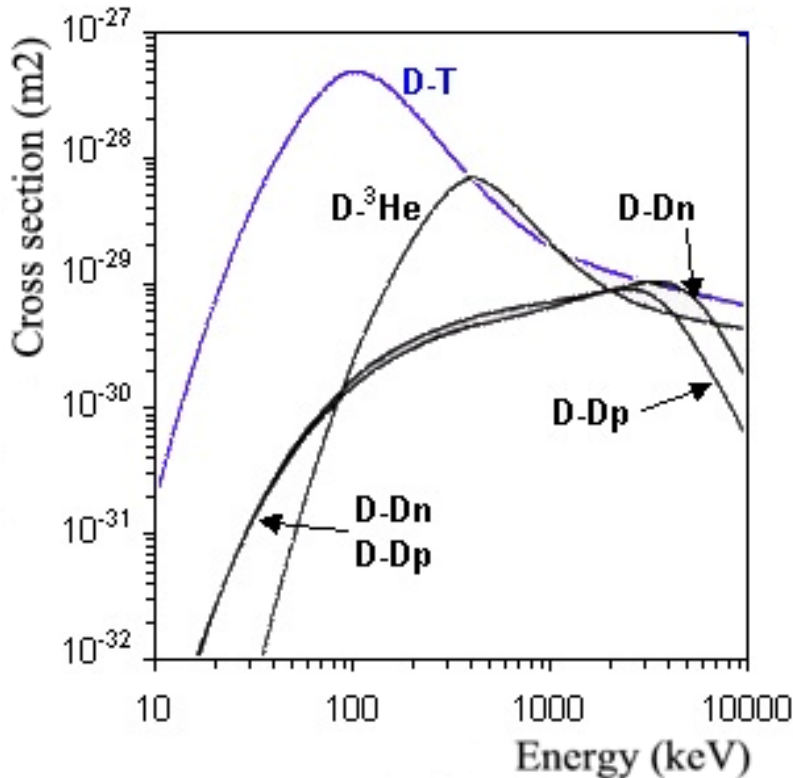
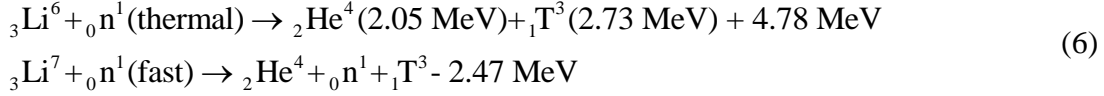


Figure 2. The cross section for the DT reaction reaches a maximum at about 100 keV at a lower value than the DHe^3 and DD reactions.

Natural lithium occurs as 7.5 percent of the ${}^6_3\text{Li}$ and 92.5 percent as the ${}^7_3\text{Li}$ isotope. An exothermic reaction can occur by thermal neutrons with the first isotope and an endothermic reaction by fast neutrons with the second isotope as follows:



The DT reaction produces neutrons that can activate the structure of the reactor, creating some radioactivity.

A fast neutron from the fusion reaction can in principle produce two tritons in these two reactions, since it is re-emitted from the fast reaction, and is available, if not absorbed by other nuclei, to induce the second reaction at low energy.

Some other potential fusion reactions with their branching ratios estimated at their cross section peaks are shown in Table 2.

Table 2: Fusion Reactions and their energy releases.

Reactants	Branching Ratios [percent]	Products	Energy yield [MeV]	Energy yield [Joule]
${}^2_1\text{D} + {}^2_1\text{D}$ (proton branch)	50	${}^3_1\text{T} (1.01 \text{ MeV}) + {}^1_1\text{p} (3.02 \text{ MeV})$	4.03	6.460×10^{-13}
${}^2_1\text{D} + {}^2_1\text{D}$ (neutron branch)	50	${}^3_2\text{He} (0.82 \text{ MeV}) + {}^1_0\text{n} (2.45 \text{ MeV})$	3.27	5.240×10^{-13}
${}^2_1\text{D} + {}^3_1\text{T}$		${}^4_2\text{He} (3.54 \text{ MeV}) + {}^1_0\text{n} (14.06 \text{ MeV})$	17.60	2.818×10^{-12}
${}^2_1\text{D} + {}^3_2\text{He}$		${}^4_2\text{He} (3.66 \text{ MeV}) + {}^1_1\text{p} (14.6 \text{ MeV})$	18.3	2.930×10^{-12}
${}^3_1\text{T} + {}^3_1\text{T}$		${}^4_2\text{He} + 2 {}^1_0\text{n} + 11.3 \text{ MeV}$	11.3	1.810×10^{-12}
${}^3_2\text{He} + {}^3_1\text{T}$	51	${}^4_2\text{He} + \text{p} + {}^1_0\text{n} + 12.1 \text{ MeV}$	12.1	1.940×10^{-12}
	43	${}^4_2\text{He} (4.8 \text{ MeV}) + {}^2_1\text{D} (9.5 \text{ MeV})$	14.3	2.292×10^{-12}
	6	${}^5_2\text{He} (2.4 \text{ MeV}) + {}^1_1\text{p} (11.9 \text{ MeV})$	14.3	2.292×10^{-12}
${}^1_1\text{p} + {}^6_3\text{Li}$		${}^4_2\text{He} (1.7 \text{ MeV}) + {}^3_2\text{He} (2.3 \text{ MeV})$	4.02	6.440×10^{-13}
${}^1_1\text{p} + {}^7_3\text{Li}$	20	$2 {}^4_2\text{He} + 17.3 \text{ MeV}$	17.3	2.773×10^{-12}
	80	${}^7_4\text{Be} + {}^1_0\text{n} - 1.6 \text{ MeV}$	-1.6	-2.565×10^{-13}
${}^2_1\text{D} + {}^6_3\text{Li}$		$2 {}^4_2\text{He} + 22.4 \text{ MeV}$	22.4	3.391×10^{-12}
${}^1_1\text{p} + {}^{11}_5\text{B}$		$3 {}^4_2\text{He} + 8.7 \text{ MeV}$	8.68	1.390×10^{-12}
${}^1_0\text{n}(\text{thermal}) + {}^6_3\text{Li}$		${}^4_2\text{He} (2.05 \text{ MeV}) + {}^3_1\text{T} (2.73 \text{ MeV})$	4.78	7.660×10^{-13}
${}^1_0\text{n}(\text{fast}) + {}^7_3\text{Li}$ (endothermic)		${}^4_2\text{He} (2.1 \text{ MeV}) + {}^3_1\text{T} (2.7 \text{ MeV})$	-2.47	-3.96×10^{-13}
${}^3_2\text{He} + {}^3_2\text{He}$		${}^4_2\text{He} + {}^1_1\text{p} + {}^1_1\text{p}$	12.9	2.065×10^{-12}

FUSION REACTIONS CROSS SECTIONS

As shown in Fig. 2, the fusion reaction cross sections are dependent on the temperature of the plasma or its energy in units of keV.

The total cross section in units of barns, where:

$$1 \text{ barn} = 1 \text{ b} = 10^{-24} [\text{cm}^2] \quad (7)$$

as a function of the energy E in units of keV of the incident particle, or the first particle listed as a reactant in Table 2, assuming that the target ion is at rest can be expressed as:

$$\sigma_T(E) = \frac{A_5 + [(A_4 - A_3 E)^2 + 1]^{-1} A_2}{E[e^{(A_4 E^{-1/2})} - 1]} \quad (8)$$

where the coefficients A_i are called the ‘‘Duane Coefficients,’’ and are given in Table 3 for some fusion reactions.

Table 3. Duane coefficients for some fusion reactions.

	DD Proton branch	DD Neutron branch	DT	DHe ³	TT	THe ³
A ₁	46.097	47.88	45.95	89.27	38.39	123.1
A ₂	372.0	482.0	50,200.0	25,900.0	448.0	11,250.0
A ₃	4.36x10 ⁻⁴	3.08x10 ⁻⁴	1.368x10 ⁻²	3.98x10 ⁻³	1.02x10 ⁻³	0.0
A ₄	1.220	1.177	1.076	1.297	2.09	0.0
A ₅	0.0	0.0	409.0	647.0	0.0	0.0

Averaged over a Maxwellian distribution, the fusion cross sections are expressed in terms of the product:

$$\overline{\sigma v} \left[\frac{\text{cm}^3}{\text{sec}} \right],$$

which is given in Table 4 as a function of the plasma temperature in keV.

Table 4. Maxwellian averaged cross section and speed product for different fusion reactions.

Plasma Temperature [keV]	$\overline{\sigma v} \left[\frac{\text{cm}^3}{\text{sec}} \right]$				
	DD	DT	DHe ³	TT	THe ³
1	1.5x10 ⁻²²	5.5x10 ⁻²¹	1.0x10 ⁻²⁶	3.3x10 ⁻²²	1.0x10 ⁻²⁸
2	5.4x10 ⁻²¹	2.6x10 ⁻¹⁹	1.4x10 ⁻²³	7.1x10 ⁻²¹	1.0x10 ⁻²⁵
5	1.8x10 ⁻¹⁹	1.3x10 ⁻¹⁷	6.7x10 ⁻²¹	1.4x10 ⁻¹⁹	2.1x10 ⁻²²
10	1.2x10 ⁻¹⁸	1.1x10 ⁻¹⁶	2.3x10 ⁻¹⁹	7.2x10 ⁻¹⁹	1.2x10 ⁻²⁰

20	5.2×10^{-18}	4.2×10^{-16}	3.8×10^{-18}	2.5×10^{-18}	2.6×10^{-19}
50	2.1×10^{-17}	8.7×10^{-16}	5.4×10^{-17}	8.7×10^{-18}	5.3×10^{-18}
100	4.5×10^{-17}	8.5×10^{-16}	1.6×10^{-16}	1.9×10^{-17}	2.7×10^{-17}
200	8.8×10^{-17}	6.3×10^{-16}	2.4×10^{-16}	4.2×10^{-17}	9.2×10^{-17}
500	1.8×10^{-16}	3.7×10^{-16}	2.3×10^{-16}	8.4×10^{-17}	2.9×10^{-16}
1,000	2.2×10^{-16}	2.7×10^{-16}	1.8×10^{-16}	8.0×10^{-17}	5.2×10^{-16}

At low plasma energies with $T \leq 25 \text{ keV}$, the data may be approximated for the DD and DT reactions by the two equations:

$$(\bar{\sigma v})_{DD} = 2.33 \times 10^{-14} T^{-2/3} e^{(-18.76T^{-1/3})} \left[\frac{\text{cm}^3}{\text{sec}} \right] \quad (9)$$

$$(\bar{\sigma v})_{DT} = 3.68 \times 10^{-12} T^{-2/3} e^{(-19.94T^{-1/3})} \left[\frac{\text{cm}^3}{\text{sec}} \right] \quad (10)$$

PLASMA POWER DENSITY

The power density released in the form of charged particles, in the DD, DT and DHe³ reactions are:

$$P_{DD} = 3.3 \times 10^{-13} n_D^2 (\bar{\sigma v})_{DD} \left[\frac{\text{Watts}}{\text{cm}^3} \right], \quad (11)$$

(including the subsequent DT reaction).

$$P_{DT} = 5.6 \times 10^{-13} n_D n_T (\bar{\sigma v})_{DT} \left[\frac{\text{Watts}}{\text{cm}^3} \right] \quad (12)$$

$$P_{DHe^3} = 2.9 \times 10^{-12} n_D n_{He^3} (\bar{\sigma v})_{DHe^3} \left[\frac{\text{Watts}}{\text{cm}^3} \right]. \quad (13)$$

FUSION APPROACHES

INERTIAL CONFINEMENT FUSION (ICF)

One approach to achieving the necessary conditions for fusion on Earth is to exploit the inertia or mass of the fusing nuclei. Inertial fusion involves the firing many times per second of high energy particle or laser beams from all directions at tiny solid fuel pellets in a reaction chamber. Material ablated off the pellet by the high energy beams drives a shock wave towards the pellet centre through an inverse rocket or implosion process, raising its temperature and density. This implosion leads to sufficient fusion reactions occurring to overcome the losses, and a large amount of energy is released in a micro-explosion. The resulting alpha particles,

neutrons, and radiation flows radially out towards the reaction chamber walls. These are situated far enough typically meters away and built so as to be able to withstand the shock loading.

Inertial fusion has been developed up to now with the main interest in the fact that it produces an excellent analog of the explosion of a nuclear weapon on a small scale, and therefore can provide a test bed for equipment resilience in such an event, without the need for a weapons test. Increasingly, this interest is being supplemented by investigations of its use for power production. The major experiment worldwide is the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in the USA.

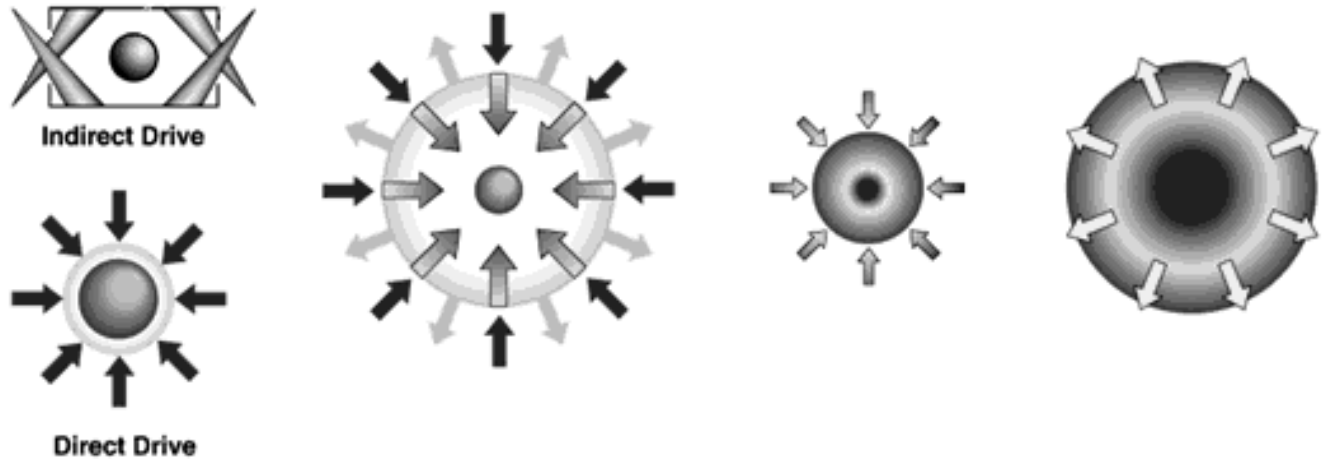


Figure 3. Steps of inertial confinement fusion reaction using direct or indirect fusion pellets.
Source: LLNL.

The laser implosion process involves the following steps:

- 1. Atmosphere formation:** Lasers or particle beams heat the surface of a fusion target in the direct drive concept, or heat the inside of a hohlraum chamber in the indirect drive concept using soft x rays, forming a plasma envelope.
- 2. Illumination:** The laser light is converted into soft x rays inside the hohlraum in the indirect drive approach, or on the outside of the direct drive pellet.
- 3. Compression:** The fuel is imploded by an inverse rocket process in the direct drive approach, or the x rays in the hohlraum implode the inner fuel surface of the pellet. The fuel core can reach 20 times the density of Pb.
- 4. Ignition:** The compressed fusion fuel ignites at about a 100 million degrees Kelvin.
- 5. Burn propagation:** The thermonuclear burn spreads through the compressed fuel, yielding several times the input energy.

MAGNETIC CONFINEMENT

An alternative approach exploits the interaction of charged particles with magnetic fields. Charged particles are deflected by a magnetic field and, if the field is strong enough, particles will orbit round a field line, gradually progressing along it if they have some longitudinal velocity. This feature forms the basis of magnetic confinement fusion, which has been under investigation since the 1950s.

PLASMA GENERATION

With increasing temperature, all materials are successively transformed from the solid to the liquid and then to the gaseous state. If the temperature is further increased, one gets plasma, the fourth state of matter. The atoms of the gas decompose into their constituents, electrons and nuclei. The name plasma was introduced by Langmuir thinking of an analogy to the plasma of a biological cell surrounded by a membrane as the plasma sheath.

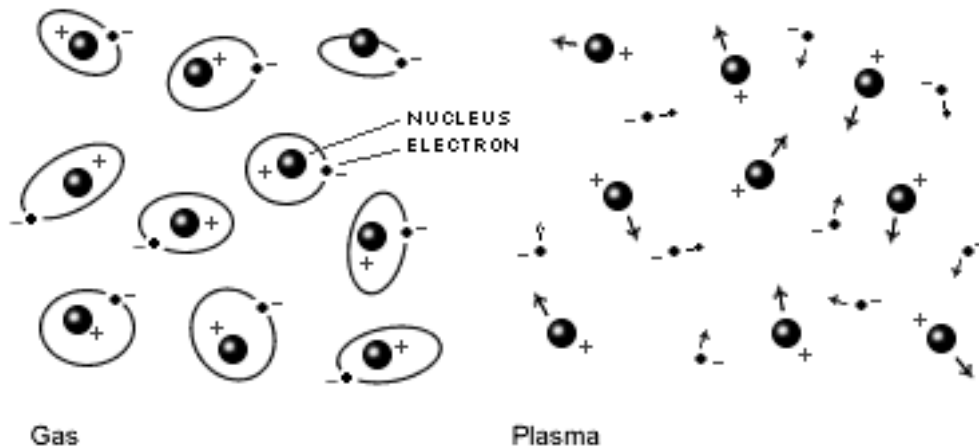


Figure 4. Generation of a plasma through heating the nuclei of a gas to the level of ionization.

Everyday examples are the plasma column in a neon tube, an electric spark or the plasma streak of lightning. The properties of a plasma are very different from those of ordinary gases. A plasma is, for example, electrically conductive. Its motion can therefore be influenced by electric and magnetic fields. This property is exploited in fusion devices by confining the hot plasma in a magnetic bottle, thereby keeping it away from the material walls Fig. 5.

LORENTZ EQUATION

The motion of charged particles in an electromagnetic field with electric field component E and magnetic field component B is described by the Lorentz equation for the force F exercised on an ion of charge q as:

$$\vec{F} = q\vec{E} + \frac{q}{c}\vec{v} \times \vec{B} \quad (14)$$

where: c is the speed of light,
 \bar{v} is the velocity of the ion,
 q is the charge of the ion.

In the absence of the electric field the vector cross product results in the charged particle rotating around the magnetic field lines in a radius R with the Lorentz force countered by the centrifugal force as:

$$\bar{F} = \frac{q}{c} \bar{v} \times \bar{B} = \frac{mv^2}{R} \quad (15)$$

Dropping the vector notation, the gyro radius of the charged particle can be deduced as:

$$R = \frac{mvc}{qB} \quad (16)$$

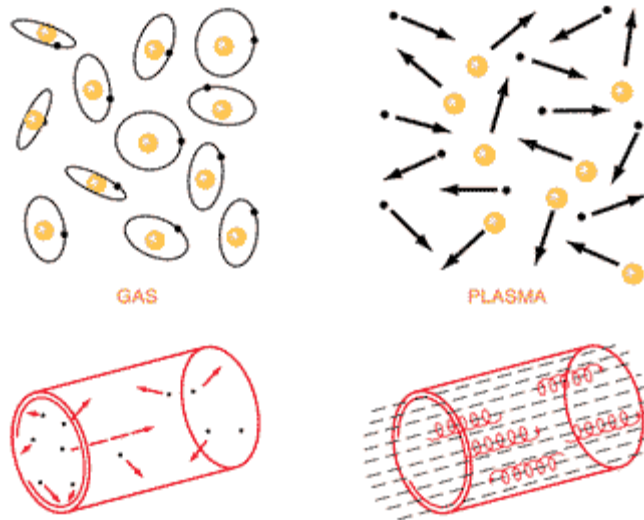


Figure 5. The motion of charged ions can be confined by a magnetic field.

The gyro radius R is proportional to the mass of the charged particle m . Consequently in a hydrogen plasma, the hydrogen ions will have larger gyro radii than the electrons. Being of opposite charges, the electrons and the hydrogen ions will rotate around the magnetic field lines in opposite directions.

MAGNETIC FIELD CONFIGURATIONS

Owing to its high temperature a fusion plasma cannot be confined directly in material vessels. Any wall contact would immediately cool down the thin gas generated in a vacuum and in the process generating a hole in the plasma container destroying the vacuum as well as the

container wall. The problem is avoided by using magnetic fields, which confine and thermally insulate the plasma, keeping it away from the vessel walls.

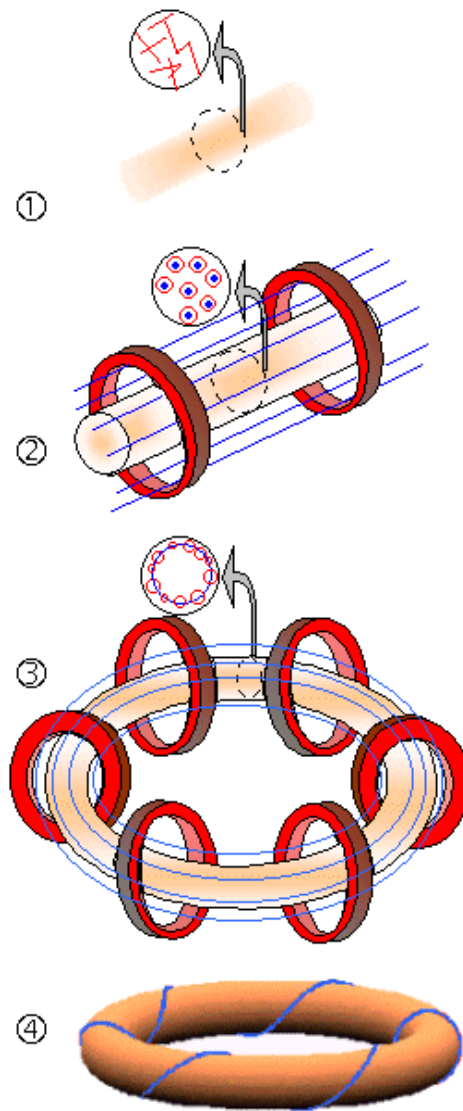


Figure 6. Ion trajectories without a magnetic field, with a linear magnetic field, and a closed field configuration.

Charged particles, both ions and electrons, are confined in a magnetic field into circular and helical orbits around the magnetic field lines. The particles are thus tied to the field lines. However, they are able to move freely in the longitudinal direction of the lines. In a suitably shaped magnetic field bottle it is therefore possible to confine a plasma and keep it away from the container wall.

Magnetic fields circularly closed upon themselves are particularly interesting. This alone is not sufficient, however, to achieve particle confinement. As the field strength in a purely ring-shaped field decreases to the outside, the particles would quickly diffuse to the wall.

As a remedy the field lines can be twisted into a helical configuration to allow permanent confinement of the plasma. The field lines enclosing the ring set up magnetic surfaces, nested in one another like layers of an onion, in which the density and temperature of each are constant.

In addition, the absence of a radial field component, which would lead to the plasma particles diffusion to the outside, is a prerequisite for magnetic plasma confinement. This is achieved by adding coils that generate a vertical magnetic field negating the tendency of the plasma to drift outward from the region of higher magnetic field on its inside to the region of weaker magnetic field on its outside.

FUSION POWER PLANTS

In the most likely scenario for a fusion power plant, a DT fuel mixture would be admitted to the evacuated reactor chamber and there ionized and heated to thermonuclear temperatures. The fuel is held away from the chamber walls by magnetic forces long enough for a useful number of reactions to take place.

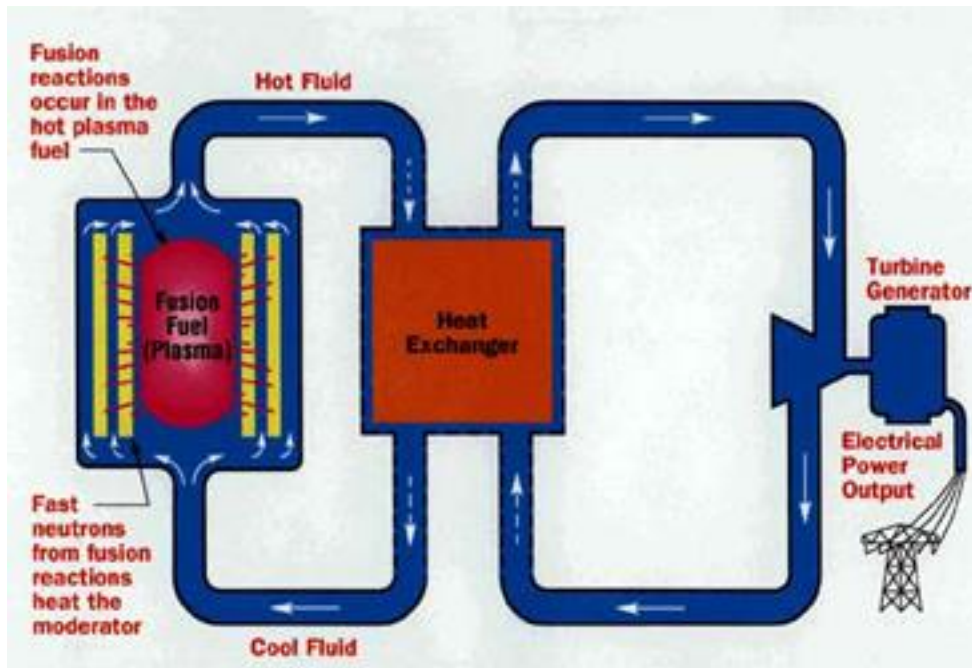
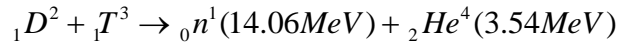
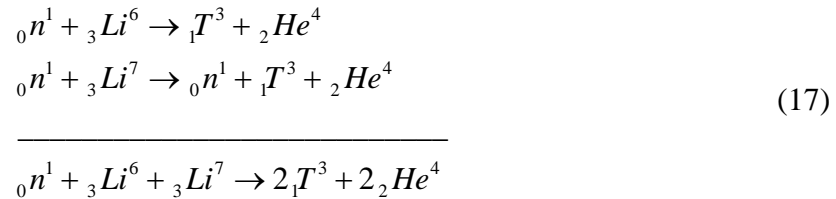


Figure 7. Electricity generation from a fusion power plant. Source: LLNL.

The charged helium nuclei which are formed give up their kinetic energy by colliding with newly injected cold fuel atoms which are then ionized and heated, thus sustaining the fusion reaction. The neutrons, having no charge, move in straight lines through the thin walls of the vacuum chamber with little loss of energy.

The neutrons and their 14.06 MeV of energy are absorbed in a blanket containing lithium which surrounds the fusion chamber. The neutrons lose their kinetic energy through collisions with liquid lithium as a coolant, thus creating heat that is removed by a heat exchanger which conveys it to a conventional steam electric plant.

The neutrons themselves ultimately enter into nuclear reactions with the two isotopes of lithium Li^6 and Li^7 to generate tritium which is separated and fed back into the reactor as a fuel:



The successful operation of a fusion power plant will require the use of materials resistant to energetic neutron bombardment, thermal stress, and magnetic forces.

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

Safety precautions are necessary because of the radioactive tritium and high-energy neutrons, which activate the walls of the plasma vessel. A fusion power plant has a unique feature: It can be designed in such a way that it does not contain any energy sources that, should they get out of control, could destroy the fusion plant from the inside.

A fusion power plant cannot undergo a runaway energy release. In the combustion chamber there is always just as much fuel burning as is actually needed: about one gram of deuterium and tritium distributed in a volume of about 1,000 cubic meters. The extremely diluted fuel, despite the high temperature, therefore has a low power density, comparable to that of an ordinary light bulb.

The radioactive fuel constituent, tritium, must be safely confined. What is released from the power plant in normal operation to the most highly exposed person is equivalent to about one per cent of the natural radioactive effective radiation dose. Even after a major accident the limit values for introducing evacuation procedures are far from reached.

Remaining as radioactive wastes are the activated walls of the plasma vessel, which have to be placed in intermediate storage upon termination of operation of a reactor plant. Its activity decreases rapidly after about 100 years to one thousandth of its initial value. After a decay time of one hundred to five hundred years the radiotoxic content of the waste is comparable to the hazard potential of the ash from a coal fired power plant, which contains radioactive substances. If special materials with low activation potential are used, a major part of the materials could be recycled and reused.

FUSION FOR SPACE PROPULSION

The travel time from earth orbit to the planet mars could be reduced from six months to less than six weeks if a nuclear fusion powered rocket is used. A fusion rocket would have a higher specific impulse that could be 300 times the thrust of any chemical rocket engine and use

only a fraction of its fuel mass. Interplanetary missions would no longer need to wait for a shortest journey launch window.

The idea is to sustain an on-board fusion reaction and exhaust the charged particles created out the back of the spacecraft, generating thrust. The reaction would not need to go far beyond the break-even point to generate thrust. Containment is less of a problem because one actually wants some of the plasma to escape (Fig. 8).

A problem is that heating the plasma to 100 million K is not hot enough to generate thrust. At that temperature, the DT fusion reaction generates 80 percent of its energy in the form of the kinetic energy of neutrons, which are uncharged and therefore cannot be steered and fired through a magnetic jet nozzle.

To produce thrust, it is preferable to use a neutronless or aneutronic fusion reaction such as the DHe³ reaction:

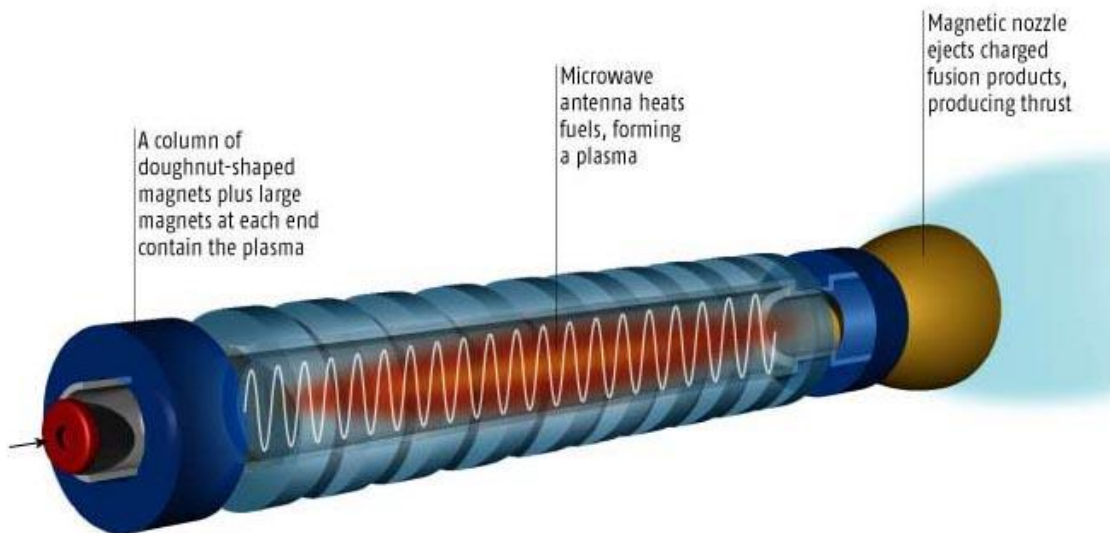
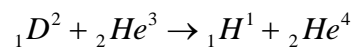


Figure 8. Conceptual fusion rocket engine. Source: LLNL.

Microwaves could be used to heat the plasma to 600 million °K, triggering such a fusion reaction that generates not neutrons but charged particles which can be steered by a magnetic field about 100 meters in length through a nozzle to propel the space craft forward. The surface of the moon is rich in He³ that was deposited by the solar wind, which could be mined from a lunar base there.

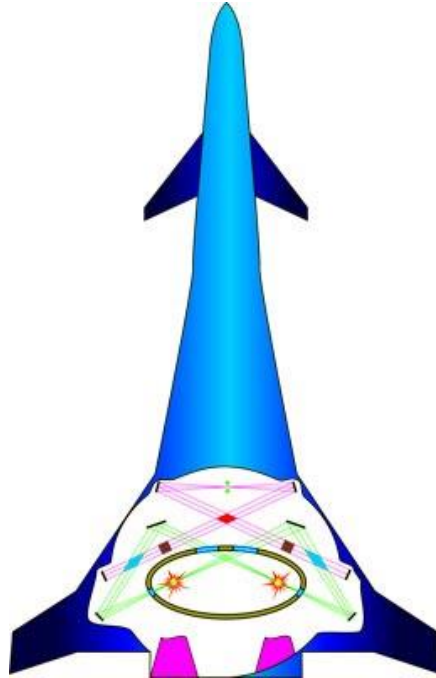


Figure 9. Inertial confinement concept for interstellar rocket propulsion.

Inertial confinement could also be used for rocket propulsion. A conceptual laser driven spaceship for interstellar propulsion system is shown in Fig. 9. Hydrogen gas as a propellant would be heated by the fusion reactions occurring inside an ellipsoid of revolution, or whispering gallery. The energy release from a pellet implosion at one of its foci would be channeled to implode another pellet at the other focus, and the process repeated much like an internal combustion engine.

WHISPERING GALLERY

The Whispering Gallery is a marvel of sound wave communication. It is formed in the form of an ellipsoid of revolution. A person standing at one of the foci can hear a person whispering at the other focus, but nowhere else.

It uses the reflective properties of conical sections. If light or sound waves are emitted from one focus of the ellipsoid, they are reflected from the wall to the other focus.



Figure 10. Whispering Gallery at the Museum of Science and Industry (MSI), Chicago, Illinois.

The Whispering Gallery at the Museum of Science and Industry (MSI), Chicago, Illinois, is constructed in the form of an ellipsoid of revolution, with a parabolic dish at each focus. It was constructed in 1937 and opened as a permanent exhibit around 1938. The width of the ellipse is 13' 6", its length is 47' 4" and the distance between the foci is 40' 7". When a person stands at one focus and whispers, the line of sound emanating from this focus reflects directly to the focus at the other end of the room, and to the other person standing there.

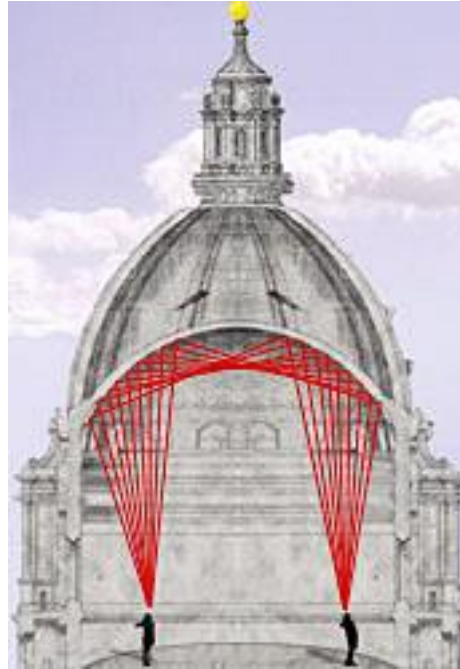


Figure 11. Whispering Gallery ceiling at the St. John Cathedral, London.

There exists a famous whispering gallery along the base of the dome of St. Paul's Cathedral in London.

The USA Senate's Capitol building in Washington, DC, also contains a room designated as Statuary Hall that has a parabolic reflecting ceiling. A tale exists that John Quincy Adams would sit at his desk that was situated at the focal point of the ceiling, and he could overhear conversations between unsuspecting subjects from different points around the room.

THE CARTESIAN OVAL

The Cartesian Oval is the geometrical figure that can refocus the emissions of radiation emitted from one of its foci to the other focus. It allows for the radiation absorbed and reemitted at its reflecting walls to change its wavelength, energy or speed from v_1 to v_2 . This allows for instance for hard x rays to be reemitted as soft x rays. An element of its use as a whispering gallery is to intercept any unreflected rays moving directly from one focus to the other by a shield placed between them.

According to Fermat's principle of optics, the time that it takes a ray to move from one focus to the wall and then to the other focus is a minimal value:

$$\tau_1 + \tau_2 = \text{Minimum} \quad (18)$$

The time that it takes the ray originating from the first focus to the point on the wall W is equal to the integral along its path of the element of length ds , divided into its velocity v_1 . Similarly the time that it takes the reflected ray to travel from the point of reflection W to the second focus

is equal to the path integral divided into its velocity v_2 . This reformulates Fermat's and Huygen's principles as:

$$\int_{F_1}^W \frac{ds}{v_1} + \int_W^{F_2} \frac{ds}{v_2} = \text{Minimum} \quad (19)$$

For constant values of the two velocities this is satisfied by the relation:

$$\frac{r_1}{v_1} + \frac{r_2}{v_2} = \text{Constant} \quad (20)$$

The general form for the Cartesian Oval can be written as:

$$\alpha r_1 + \beta r_2 = C$$

(21)

where: $\alpha \neq \beta$

EXAMPLE

If hard x rays with a high energy and speed are absorbed than reemitted by the reflecting surface as soft x rays at a lower energy and speed, then we can take as an example:

$$v_2 = \frac{1}{2} v_1$$

Then the equation of the Cartesian Oval becomes:

$$\frac{r_1}{v_1} + \frac{2r_2}{v_1} = C$$

Since v_1 is a constant itself, it ensues that:

$$r_1 + 2r_2 = C'$$

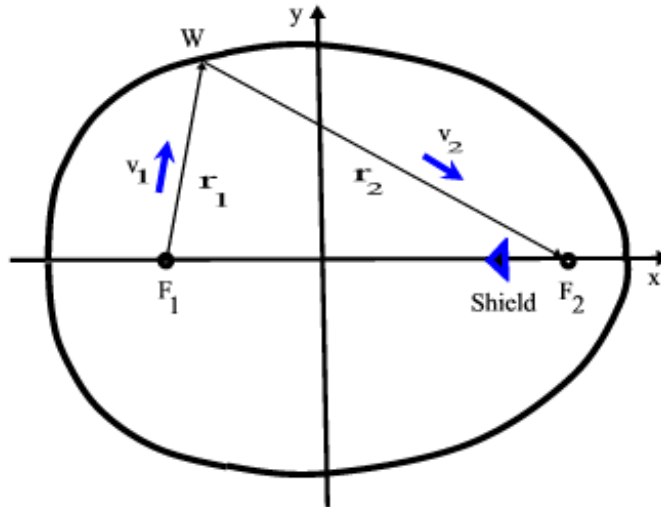


Figure12. The Cartesian Oval.

THE ELLIPSOID OF REVOLUTION

The ellipsoid of revolution is a special case of the Cartesian Oval in which the velocities of the incident and reflected rays are the same v :

$$v_1 = v_2 = v$$

Consequently the equation of the ellipsoid becomes:

$$\frac{r_1}{v} + \frac{r_2}{v} = \text{Constant}$$

This can be written in the simple form:

$$r_1 + r_2 = C'' \tag{22}$$

This expresses the fact that in this case the total distance traveled by the rays from one focus to the other remains constant.

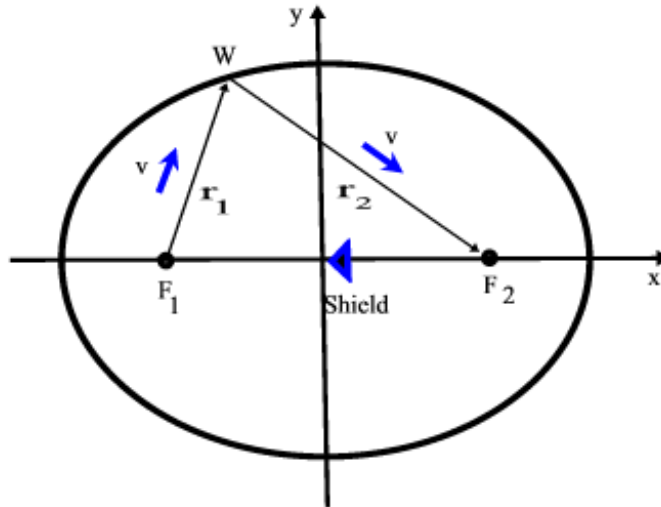


Figure 13. The Ellipsoid is a special case of the Cartesian Oval.

FUSION DRIVEN SUBCRITICAL FISSION

The transmutation and incineration of various long lived isotopes as actinides and fission products in fission reactors is a possibility using subcritical assemblies driven by an external neutron source. Particle accelerators using a uranium target can generate a spallation source for such transmutation. Another alternative is to use a DT plasma as a neutron source. The potential advantages of this approach as compared to critical fast reactors are:

1. A higher flexibility regarding the form of the actinide fuel and coolant.
2. Attainment of a maximum net burning of actinides.
3. Enhanced safety characteristics.

A subcritical fission blanket with 14.06 MeV neutrons from a DT plasma source offers advantages when compared to other subcritical concepts. The 14.06 MeV neutrons offer additional flexibility with regard to, the neutron economy from the generation of additional neutrons from (n,2n), (n,3n), and other threshold nuclear reactions. This allows even lower k_{eff} regimes. The volumetric nature and associated lower power density of the plasma neutron source as compared to a spallation neutron source opens new design possibilities for the subcritical fission blanket.

The technical demands on a DT fusion-plasma neutron source are lower by more than an order of magnitude compared to those of a pure fusion system. This reduction in technical demands is thought to lead to lower costs and feasibility for a fusion-fission hybrid as compared to pure fusion or pure fission systems.

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EXERCISE

1. Compare the Maxwellian averaged cross sections as well as the associated power densities at plasma temperatures of 10 and 100 keV and a density of 10^{10} [ions/cm³] for the following fusion reactions:
 1. DD fusion reaction
 2. DT fusion reaction