1
Introduction

1.1
Basics of Fusion

Fusion has the potential of providing an essentially inexhaustible source of energy for the future. Under the proper conditions the low atomic number elements will react to convert mass to energy [$E = (\Delta m)c^2$] via nuclear fusion. For example, the fusion of the hydrogen isotopes deuterium (D) and tritium (T) according to the reaction

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He} + n \quad (Q = 17.6\,\mathrm{MeV})$$

produces 17.6 MeV of energy.

The fusion of 1 g of tritium (together with $\frac{2}{3}$ g of deuterium) produces 1.6×10^5 kW-hr of thermal energy. Deuterium exists at 0.0153 at.% in sea-water and is readily extractable, thus constituting an essentially infinite fuel source. Tritium undergoes beta decay with a half-life of 12.5 yr. Thus it must be produced artificially, for example, by neutron capture in lithium. (Natural lithium consists of 7.5% ^{6}Li and 92.5% ^{7}Li and is quite abundant in nature). The tritium production reactions are

$$n + {}^6\mathrm{Li} \rightarrow \mathrm{T} + {}^4\mathrm{He}$$
$$n + {}^7\mathrm{Li} \rightarrow \mathrm{T} + {}^4\mathrm{He} + n'$$

The first reaction has a large cross section for thermal (slow) neutrons, while the second reaction is more probable with fast neutrons. When the lithium is placed around the fusion chamber, the fusion neutrons can be used to produce tritium, thereby introducing the possibility of a fusion reactor "breeding" its own fuel.

Another promising fusion reaction is

$$\mathrm{D} + \mathrm{D} \rightarrow \begin{cases} \mathrm{T} + \mathrm{H} & (Q = 4\,\mathrm{MeV}) \\ {}^3\mathrm{He} + n & (Q = 3.25\,\mathrm{MeV}) \end{cases}$$

which has two branches of roughly equal probability. With this reaction the fusion fuel source is truly inexhaustible.

A third possible fusion reaction is

$$\mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + \mathrm{H} \quad (Q = 18.2\,\mathrm{MeV})$$

There are many others involving the low atomic number elements.

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In order for a fusion reaction to take place the two nuclei must have enough energy to overcome the repulsive Coulomb force acting between the nuclei and approach each other sufficiently close that the short-range attractive nuclear force becomes dominant. Thus, the fusion fuel must be heated to high temperatures. For the D-T reaction, the gas temperature must exceed 5×10^7 K before a significant fusion rate is feasible. An even higher gas temperature is required for the other fusion reactions. At such temperatures the gas exists as a macroscopically neutral collection of ions and unbound electrons which is called a plasma.

The fusion reaction rate per unit volume can be written

$$\mathrm{R}(\text{fusions}/\mathrm{m}^3) = n_1 n_2 \langle \sigma v \rangle_{12}$$

where n_1 and n_2 are the densities of species 1 and 2, respectively, and

$$\langle \sigma v \rangle_{12} = \iint d^3 v_1 d^3 v_2 f_1(\mathbf{v}_1) f_2(\mathbf{v}_2) |\mathbf{v}_1 - \mathbf{v}_2| \sigma_f(|\mathbf{v}_1 - \mathbf{v}_2|)$$

is the fusion reactivity. Here v is the velocity, f is the velocity distribution function, and σ_f is the fusion cross section. It is usually adequate to use a Maxwellian distribution,

$$f_{\max} = \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT}$$

to evaluate $\langle \sigma v \rangle$, in which case the value of the integral depends only upon the temperature T of the plasma. The fusion reactivity is shown in Figure 1.1 for the three reactions cited above. The D-T fusion reactivity is much greater than that for other

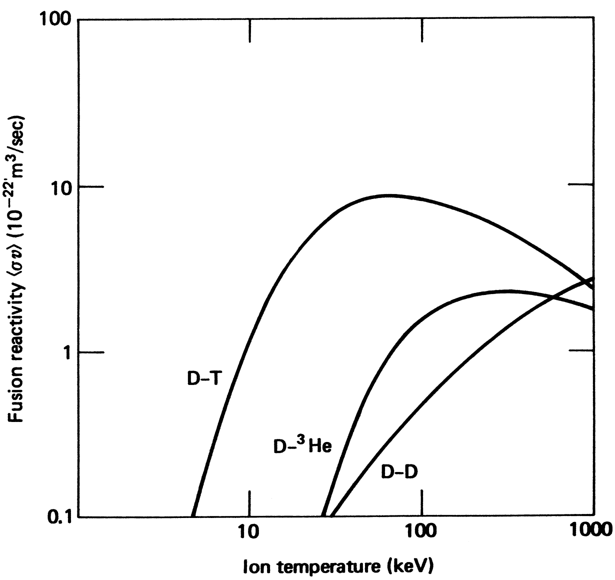

Figure 1.1 Fusion reactivity.

potential fusion reactants, which is the reason why achieving the necessary conditions for D-T fusion is the principal goal of the present phase of fusion research.

The 17.6 MeV of energy produced in the D-T fusion event is in the form of kinetic energy of the neutron (14.1 MeV) and the alpha particle (3.5 MeV). The alpha particle is confined within the plasma, and its energy is distributed via collisions among the plasma ions and electrons and eventually is incident upon the wall of the reaction chamber as a surface heat flux. The neutron leaves the plasma immediately and gives up its energy to the surrounding material via elastic and inelastic collisions with lattice atoms, producing a volume heat source and, in the process, radiation damage to the material due to atomic displacements. The fusion neutron is ultimately captured or leaks from the system. The neutron may be captured in lithium to produce tritium to sustain the fusion fuel cycle, or it may be captured in structural material, thereby producing a relatively short-lived radioactive isotope. In projected applications of fusion to produce fuel for fission reactors, the neutron may be captured in uranium-238 or thorium-232, thereby initiating nuclear transmutation chains leading ultimately to plutonium-239 or uranium-233, respectively.

Heating a plasma to thermonuclear temperatures and then confining it sufficiently well that a net positive energy balance can be achieved are the two premier issues which will determine the scientific feasibility of fusion. Experimental progress with magnetically confined plasmas has been impressive in recent years, and scientific feasibility should be convincingly established in the near future.

Beyond scientific feasibility there are several scientific and technological issues which will determine the practicality of fusion. Among the former are achieving high power density and a quasi-steady-state mode of operation. Technological issues include plasma heating systems, superconducting magnets, materials, tritium breeding blankets, vacuum systems, and remote maintenance.

1.2 Magnetic Confinement

A fusion plasma cannot be maintained at thermonuclear temperatures if it is allowed to come in contact with the walls of the confinement chamber, because material eroded from the walls would quickly cool the plasma. Fortunately, magnetic fields can be used to confine a plasma within a chamber without contact with the wall. (This statement is only approximately true, as we shall see in a later chapter).

A charged particle moving in a magnetic field will experience a Lorentz force which is perpendicular to both the direction of particle motion and to the magnetic field direction. This force does not affect the component of particle motion in the magnetic field direction, but it causes acceleration at right angles to the particle direction in the plane perpendicular to the magnetic field direction, producing a circular particle motion in that plane. Thus, a particle in a magnetic field will move along the field and circle about it; that is, will spiral about the field line. The radius of the spiral, or gyroradius, is inversely proportional to the strength of the magnetic field, so that in a strong field charged particles move along magnetic field lines, as shown in Figure 1.2.

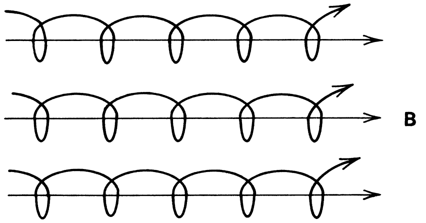

Figure 1.2 Motion of charged particles along magnetic field lines.

1.2.1
Closed Toroidal Confinement Systems

The magnetic field lines may be configured to remain completely within a confinement chamber by the proper choice of position and currents in a set of magnetic coils. The simplest such configuration is the torus, shown in Figure 1.3. A set of coils can be placed to produce a toroidal field $\mathbf{B}_{\phi}$. Particles following along the closed toroidal field lines would remain within the toroidal confinement chamber.

The curvature and nonuniformity of the toroidal field produce forces which act upon the charged particles to produce "drift" motions that are radially outward, which would, if uncompensated, cause the particles to hit the wall. A poloidal magnetic field must be superimposed upon the toroidal magnetic field in order to compensate these drifts, resulting in a helical magnetic field which is entirely contained within the toroidal confinement chamber. This poloidal field may be produced by a toroidal current flowing in the plasma (tokamak) or by external coils (stellarator, etc.).

The tokamak concept, which was invented in the U.S.S.R. in the mid-1960s, has been the most extensively investigated worldwide and is the most advanced. This

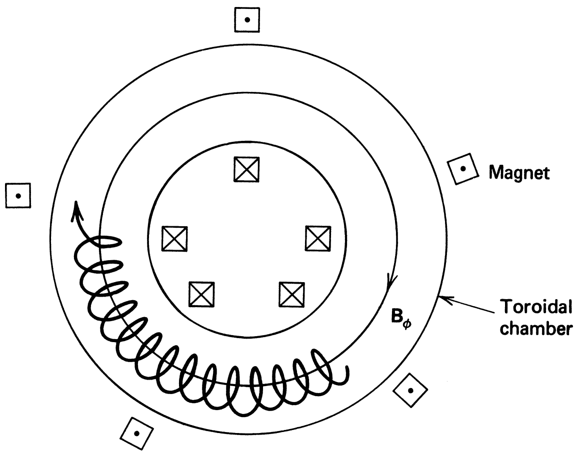

Figure 1.3 Closed toroidal confinement.

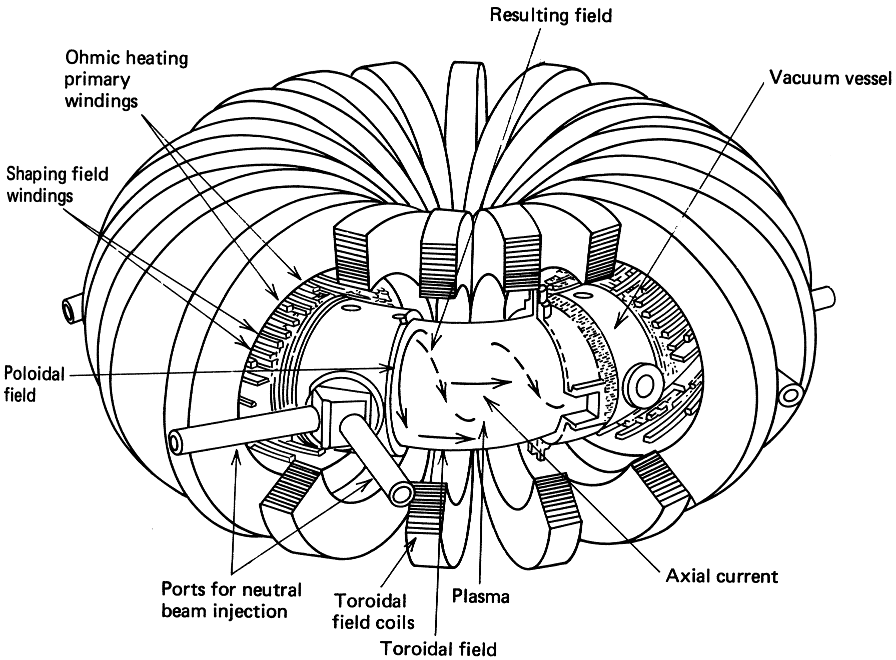

Figure 1.4 Tokamak schematic.

concept is illustrated in Figure 1.4. The toroidal field is produced by a set of toroidal field coils which encircle the plasma. The poloidal field is produced by an axial, or toroidal, current which is induced by the transformer action of a set of primary poloidal field, or ohmic heating, coils. The extensive worldwide interest in the tokamak concept is indicated by the partial lists of experiments given in Table 1.1. The relative scale of some of these devices is illustrated in Figure 1.5.

Table 1.1 Representative tokamak experiments.

Device	Major Radius (m)	Minor Radius (m)	Magnetic Field (T)	Plasma Current (MA)
T-10 (Russia)	1.5	0.37	4.5	0.7
TFTR (USA)	2.4	0.80	5.0	2.2
JET (UK)	3.0	1.25	3.5	7.0
DIII-D (USA)	1.7	0.67	2.1	2.1
ToreSupra (FR)	2.4	0.80	4.5	2.0
ASDEX-U (Ger)	1.7	0.50	3.9	1.4
JT60-U (Japan)	3.4	1.1	4.2	5.0
ALCMOD (USA)	0.7	0.22	9.0	1.1
EAST (China)	1.7	0.4	3.5	1.0
K-STAR (Korea)	1.8	0.5	3.5	2.0

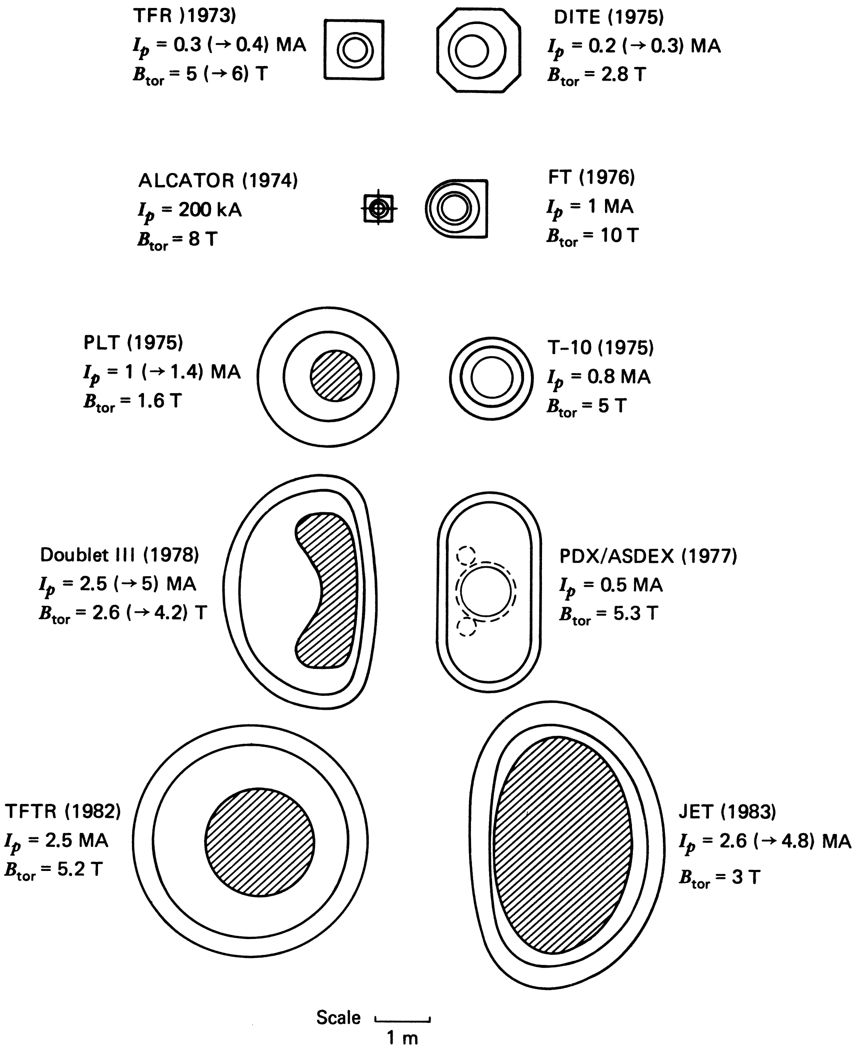

Figure 1.5 Relative size of some major tokamak devices throughout the world. Dimensions are to scale and the plasma current and the magnetic field are given in each case.

1.2.2 Open (Mirror) Confinement Systems

It is possible to confine a plasma magnetically within a fixed confinement chamber, even when the magnetic field lines themselves do not remain within the confinement chamber, by trapping the charged particles in a magnetic well. The principle is illustrated in Figure 1.6, where the particle speeds along ($v_{\parallel}$) and perpendicular to ($v_{\perp}$) the magnetic field are denoted.

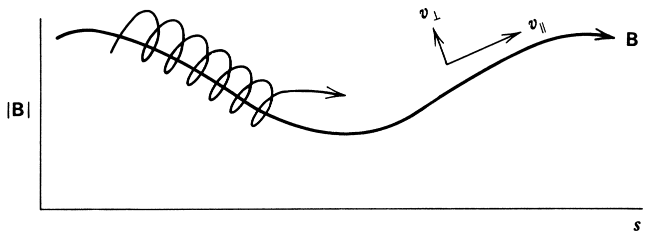

Figure 1.6 A magnetic well.

Because the force exerted on a moving charge by a magnetic field is orthogonal to the direction of particle motion, no work is done on the particle and its kinetic energy (KE) remains constant:

$$\frac{1}{2}m\left[v_\parallel^2(s)+v_\perp^2(s)\right]\equiv \mathrm{KE}=\text{constant}$$

The angular momentum is also conserved, so that

$$\frac{1}{2}\frac{mv_\perp^2(s)}{B(s)}\equiv \mu=\text{constant}$$

Thus, the velocity along the field line can be expressed as

$$v_\parallel^2(s)=\frac{2}{m}[\mathrm{KE}-\mu B(s)]$$

For particles with sufficiently large values of μ, the right-hand side (RHS) can vanish as the particle moves along the field line into a region of stronger magnetic field. When the field is strong enough that the RHS vanishes, the particle is reflected and travels back along the field line through a region of reducing, then increasing magnetic field strength until it comes once again to a reflection point, at which the field strength is again large enough to make the RHS vanish. This is the principle of the simple mirror illustrated in Figure 1.7, in which a magnetic well of the type shown in Figure 1.6 is created by ring coils carrying currents of different magnitudes.

The simple mirror is unstable against flute-type instabilities in which the plasma bulges outward in the low field regions. The flute-type instability can be suppressed by placing the plasma in a three-dimensional magnetic well. Such a "minimum-*B*" magnetic configuration can be created by a coil wound like the seams of a baseball, as shown in Figure 1.7. The minimum-*B* mirror concept is well understood based on the results of more than a dozen experiments, but the prospects for achieving a favorable power balance in a fusion reactor are not good.

Because electrons escape faster than ions, mirrors operate with a slightly positive electrostatic potential. This fact allows minimum-*B* mirrors to be used at each end of a simple central cell mirror to confine ions electrostatically in the central cell in the tandem mirror concept. The present mirror experiments in the world are indicated in Table 1.2.

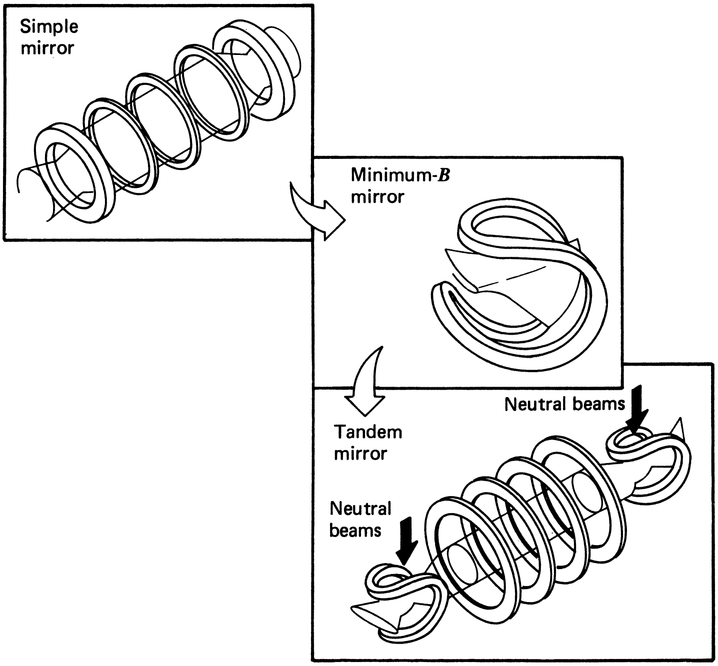

Figure 1.7 The evolution of magnetic mirrors. (Reproduced by permission of university of California, Lawrence Livermore National Laboratory, and the Department of Energy.)

Table 1.2 Mirror experiments.

Device	Country
GAMMA-10	Japan
GOL-3	Russia
GDT	Russia
AMBAL-M	Russia
HANBIT	Korea

1.3
Feasibility of Fusion

Feasibility issues can be conveniently separated into issues of scientific, engineering and economic feasibility, at least for the purpose of discussion.

1.3.1
Scientific Feasibility

Scientific feasibility basically comes down to confining a plasma at thermonuclear temperatures well enough that a sufficiently positive energy balance can be obtained to enable net power to be produced from the fusion reactions. The plasma power amplification factor

$$Q_p = \frac{\text{fusion power}}{\text{external heating power}}$$

is a conventional measure of scientific feasibility, albeit on a sliding scale. $Q_p > 1$ will constitute "breakeven" on the plasma energy balance when achieved (i.e., the plasma will be producing a larger amount of thermal power from fusion reactions than the amount of external power that must be provided in addition to the fusion power to maintain the plasma at thermonuclear temperature). The ultimate goal (actually the holy grail) of plasma physics research is the achievement of sufficiently good confinement that the 20% of the D-T fusion energy retained in the plasma in the form of an energetic alpha particle is sufficient to maintain the plasma at thermonuclear temperature without any external power; this condition of $Q_p = \infty$ is known as "ignition". However, no matter how good the confinement, future fusion reactors will operate with some external power for control purposes, so the practical definition of scientific feasibility is Q_p large enough that net electrical power can be economically produced, which is probably $Q_p > 10$.

The plasma power balance can be written as

$$\begin{gathered}\textit{fusion heating} + \textit{external heating} \geq \textit{radiation loss} + \textit{transport loss} \\ \frac{1}{4} n^2 \langle \sigma \upsilon \rangle_{fus} U_\alpha \left(1 + \frac{5}{Q_p} \right) \geq f_z n^2 L_z + \frac{3nT}{\tau_E}\end{gathered}$$

where $n = n_D + n_T$ is the total ion density, $U_\alpha = 3.5$ MeV is the energy of the alpha particle from D-T fusion, f_z and L_z are the concentration and radiation emissivity of the ions (plasma plus impurity) present, T is the plasma temperature, τ_E is the time which energy is confined in the plasma before escaping, and $\langle \sigma \upsilon \rangle_{\text{fus}} \simeq \text{const} \times T^2$ is the fusion reactivity. Neglecting the radiation term, this equation can be rearranged to obtain the Lawson criterion for ignition

$$nT\tau_E \geq \frac{12}{\text{const} \times U_\alpha} \equiv (nT\tau_E)_{\text{Lawson}}$$

The achieved values of the plasma energy amplification factor Q_p and of the triple product $nT\tau_E$ are indicated in Figure 1.8.

The triple product $nT\tau_E = p\tau_E$, indicating that achievement of power balance at high Q_p requires achieving high plasma pressure and long plasma energy confinement time. The magnitude of plasma pressure that can be achieved is related to the magnitude of the confining magnetic field pressure magnetohydrodynamic (MHD) instability limits which can be characterized in terms of limiting values of

$$\beta \equiv \frac{\textit{plasma pressure}}{\textit{magnetic pressure}} = \frac{nkT}{B^2/2\mu_0}$$

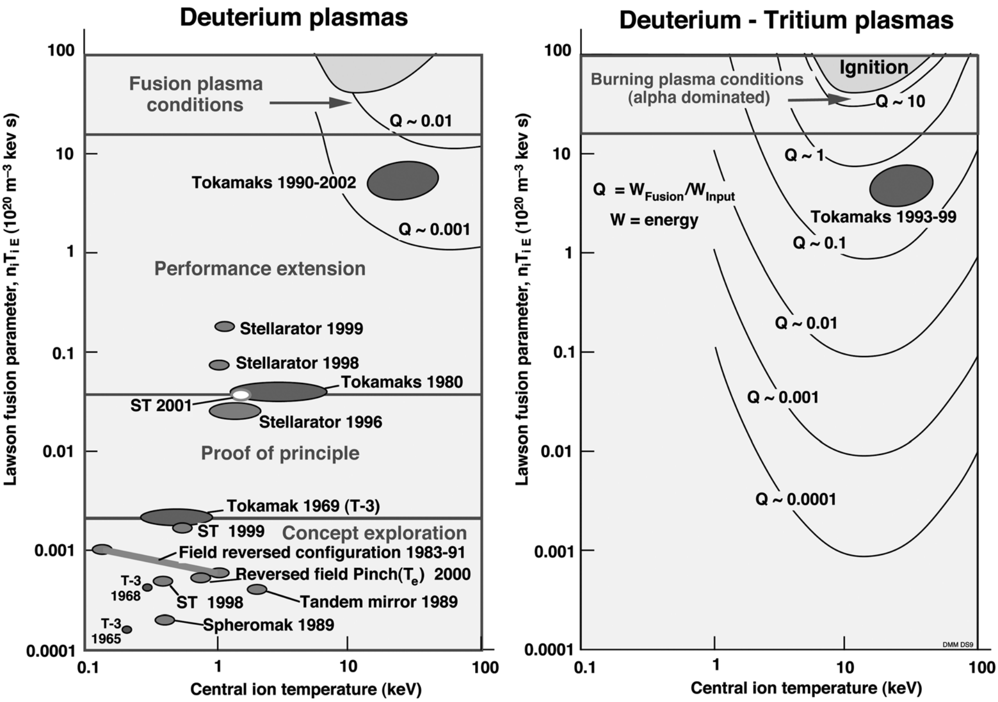

Figure 1.8 Progress towards scientific feasibility as measured by the Lawson criterion.

Since the power density in a D-T plasma can be written

$$P = \frac{1}{4} n^2 \langle \sigma \upsilon \rangle_{fus} U_{fus} \simeq \frac{1}{4} \text{const} \times (nT)^2 U_{fus} \sim \beta^2 B^4$$

a second aspect of practical scientific feasibility is the achievement of sufficiently large values of β.

1.3.2 Engineering Feasibility

The development of magnetic fusion as an energy source requires the development of two types of engineering technologies – (i) those "plasma support" technologies that are necessary to heat and confine the plasma, and (ii) those "nuclear" technologies that are necessary for a power reactor.

The plasma support technologies include the vacuum system, the magnet system, the plasma heating system, the plasma fueling system and other such systems. The development of plasma-facing components that can survive in the high particle and heat fluxes that will be incident upon them in ITER and future fusion reactors is also included. These systems are relatively highly developed as a result of magnetic fusion R&D that has been carried out world-wide in support of national fusion programs for the past 40 years and more recently in the R&D program that has been carried out for the International Thermonuclear Experimental Reactor (ITER). The operating parameters of systems that are being developed for ITER are comparable to those that will be needed for future power reactors, and ITER operation will provide a test of these technologies in a fusion reactor environment. While the requirements placed on these technologies by ITER and future reactors are certainly challenging, these challenges would appear to be more a matter of achieving reliable operation in a complex environment than of achieving a breakthrough in performance capability.

The state of development is less advanced for those "nuclear" technologies needed, in addition to reliable "plasma support" technologies, for a fusion power reactor. The technology needed to "breed" the tritium required for D-T plasma operation is being developed for testing in ITER, and the technology needed to process tritium is being developed for the operation of ITER. The heat removal and power conversion technologies needed for fusion power are similar to those needed for conventional (fission) nuclear power. The development of radiation-resistant structural materials that can be used in the intense fast neutron environment that will be present in a fusion reactor is a major challenge.

1.3.3 Practical Feasibility

The ultimate goal of fusion development – a power plant that provides power to an electrical power grid reliably and with high availability – creates some practical feasibility issues for fusion plasma physics and technology related to sustainable modes of operation. For example, since continuous or quasi-continuous operation is preferable to short-pulse operation with long down-times between pulses, the development of non-inductive current-drive techniques may be a feasibility issue for the conventional tokamak confinement concept, which is inherently pulsed. On the other hand, the requirement for very small tolerances in the manufacture of the large and very complex magnetic coils of a stellarator (which is inherently steady-state) constitutes another type of practical feasibility issue.

1.3.4 Economic Feasibility and Fuel Resources

It is possible to estimate the cost of building and operating a fusion power plant to produce electricity in the middle of the century and to compare with a similar estimate of the cost of building and operating a coal-fired or nuclear plant then, and this has been done. The cost estimate of fusion electricity is usually somewhat more expensive, using today's cost formulas. However, today's cost formulas do not include things like the cost of preventing carbon emissions into the atmosphere, or the costs of recovering more than the 1% of the energy potential of uranium that is recovered in the present "once-through" nuclear fuel cycle, or the availability into the future of the fuel resource. If the world's proven reserves of fossil fuels, uranium and lithium (source of tritium) were each "burned" at the rate required to provide all of the world's estimated electricity usage in 2050, the fossil fuels would be gone in less than 100 years, the uranium used in the present "once-through" fuel cycle would be gone by the end of the century (this could be extended to a few hundred years by the introduction of fast breeder reactors), but the lithium would last more than 6000 years.