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1. INTRODUCTION

The basic principle of the fusion process is the fusing of light nuclei to form heavier nuclei with the accompanying release of substantial energy. Controlled thermonuclear fusion is potentially a major vast new energy source suited to the industrialised world. A reactor based on nuclear fusion would be inherently safe and environmentally friendly. Furthermore, fuels are cheap, abundant and widely available.

A fusion reactor would be:

- **safe** because it would operate at low pressure, low fuel inventory and maximum reactivity. No significant surges of power would be possible since the fuel in the reactor at any time would be sufficient for only 30s of operation.
- **environmentally friendly** because it would not pollute the atmosphere and it would avoid the problems (such as "greenhouse" gases and acid rain) associated with the burning of fossil fuels. The hazard potential would be limited since there would be no long lived radioactive waste from the reaction products, including the fuel "ash". Radioactivity in the structure of the reactor would be minimised by careful selection of low-activation materials.
- **using fuels in abundant supply** because the principal fuel, deuterium, is readily available - it can be extracted from water - and supplies would last for millions of years. The first type of reactor would also use tritium which does not occur naturally but can be manufactured from lithium in the reactor itself. Lithium reserves are plentiful in the Earth's crust and could last for more than a thousand years.

Two approaches towards controlled thermonuclear fusion are being pursued at present - one based on inertial confinement and the other on magnetic confinement. A major step in the fusion programme would be the construction of the core of a first reactor. With the start of the Engineering Design Activities (EDA) of the International Thermonuclear Experimental Reactor (ITER), the magnetic confinement programme is preparing to take this step with the most advanced concept for magnetic confinement, namely the toroidal tokamak, of which the Joint European Torus (JET) is the largest in operation.

2. CONTROLLED THERMONUCLEAR FUSION

2.1 Basic Principles

The basic principle of nuclear fusion is the fusing together of light nuclei to form heavier ones and in this process a small quantity of mass is converted into a large amount of energy.

15M°C (~1.5keV) fuse together (Fig.1). The rate at which fusion occurs in the sun is relatively slow; for a fusion reactor on earth, a higher rate is required and hence much higher temperatures are needed - typically in the range of 100-200 M°C (10-20keV), which is 10 times greater than the temperature in the centre of the Sun. In addition, in a reactor, a high enough concentration (or density) of fuel must be maintained at these temperatures for sufficient periods. For a reactor, there are, in pronciple, several possible fusion reactions, but the one that is easiest to achieve is that between the two isotopes of hydrogen - deuterium (D) and tritium (T) (Fig.2). Deuterium can be easily and cheaply obtained from water and tritium can be manufactured in a fusion reactor from the light metal lithium. The reactions involved are:

Fusion Reaction	$D + T \rightarrow {}^4He + n$
Tritium Breeding Reactions	${}^6Li + n \rightarrow T + {}^3He$
	${}^7Li + n \rightarrow T + {}^4He + n$

2.2 Magnetic Confinement

At the temperatures needed for this reaction to occur, the D-T fuel is in the plasma state, comprising a mixture of charged particles (nuclei and electrons). In a reactor, there must be sufficient fuel present and the energy losses must be kept sufficiently low to ensure that more energy is released from the fusion reaction than is needed to heat the fuel and maintain the necessary temperature. The plasma nuclei can be contained by gravitational forces, as in the sun, or by magnetic fields. For magnetic confinement, the effectiveness of the magnetic field in containing plasma and minimising thermal losses can be measured by the time taken for the plasma to cool down after the source of heat is removed. This is called the energy confinement time and needs to be between one and two seconds in a reactor - although the plasma will be contained for considerably longer. The power output depends on the amount (or density) of fuel present, which is only a few thousandths of a gram per cubic metre, but is sufficient to yield vast amounts of energy. Thus a fusion reactor must produce high temperature plasmas of sufficient density and contain them for long enough to generate a net output of power.

For a D-T fusion reactor, the triple product of the temperature (T_i), density (n_i) and energy confinement time (τ_E) must exceed the value ($n_i.\tau_E.T_i$) of $5 \times 10^{21} m^{-3} skeV$. Typically, for magnetic confinement concepts, this requires:

Central ion temperature,	T_i	~	10-20keV
Central ion density,	n_i	~	$2\text{-}3 \times 10^{20} m^{-3}$
Global energy confinement time,	τ_E	~	1 - 2s

3. THE TOKAMAK APPROACH TO MAGNETIC CONFINEMENT

3.1 The Tokamak Concept

The tokamak is the most advanced concept for containing magnetically a hot dense plasma . It originated in the USSR and JET is the largest device in operation. A toroidal, axisymmetric plasma is confined by the combination of a large toroidal magnetic field, and a smaller poloidal magnetic field (created by a toroidal current through the plasma). The position and shape of the plasma cross-section is determined by magnetic fields generated by further toroidal coils external to the plasma (Fig.3).

The current circulating in the tokamak heats the plasma resistively. However, temperatures are limited by the decrease in resistivity of the plasma with increasing temperature. Auxiliary heating is then required to reach higher temperatures; for example, the injection of beams of high energy neutral particles; and electromagnetic waves in different frequency ranges, such as ion cyclotron resonance heating and lower hybrid heating. In a fusion reactor, collisional heating is dominant as the high energy alpha-particles (^{4}He) created during the fusion process thermalize with the background plasma.

The heating effectiveness is determined by the thermal insulation of the plasma measured by the energy confinement time. Unfortunately, energy confinement is worse than would be expected on the basis of kinetic theory with binary collisions between particles (the so-called neo-classical theory) and a theoretical model for the anomalously poor insulation is needed. Empirical scaling laws for the energy confinement time have been derived on the basis of statistical fits to experimental data. The scalings which characterize discharges with additional heating (the low confinement or L-regime) are quite different from, and more pessimistic than, those for resistive (or ohmic) heating alone. However, the expectations of L-regime scalings have been exceeded by up to a factor of about three in some regimes of plasma operation, the most notable of which is the H-regime (or high confinement mode).

The main methods of increasing the plasma density are: edge fuelling by the injection of cold gas and low speed frozen solid pellets; and central fuelling by high energy neutral particles and high speed frozen solid pellets.

The plasma environment and the system chosen to define the plasma edge and to exhaust particles and energy is also important. The first-wall that the plasma encounters can be a copious source of impurities to cool and poison the hot plasma. Therefore, a careful choice of configuration and first-wall material must be made, as this determines the extent of the impurity problem. One option is a material limiter, in which a solid structure defines the plasma boundary. An alternative is a poloidal magnetic divertor (X-point configuration), in which the plasma boundary is defined by the transition between closed, nested magnetic surfaces and open magnetic field lines, which eventually intersect target plates away from the main plasma.

3.2 The Tokamak Programme towards a Reactor

During the early 1970's, it was clear that the achievement of near-reactor conditions required much larger machines, which were likely to be beyond the resources of individual countries. In 1973, it was decided in Europe that a large device, the Joint European Torus (JET), should be built as a joint venture.

JET is the largest project in the coordinated programme of EURATOM, whose fusion programme is designed to lead ultimately to the construction of an energy producing reactor.

Its strategy is based on the sequential construction of major apparatus such as JET, a Next Step device, and a demonstration reactor, supported by medium sized specialized tokamaks.

The objective of JET is to obtain and study plasma in conditions approaching those needed in a thermonuclear reactor. By mid-1983, the construction of JET was completed on schedule and the research programme started. To date, JET (Fig.4) has successfully contained plasmas of thermonuclear grade, and reached near breakeven conditions in single discharges. These results have also produced a clearer picture of energy and particle transport, providing the basis for developing a model which describes and predicts plasma behaviour.

Furthermore, moderate extrapolation of latest results and considerations of model predictions allow the size and performance of a thermonuclear reactor to be largely defined. Most critical for a reactor is the control of impurities and the exhaust of fuel "ash" at high power. To consolidate the model and provide further information on density and impurity control, a New Phase of JET is underway. A Next Step device, such as ITER, will then bridge the gap from present knowledge to that required to construct a demonstration reactor.

4. STATUS OF TOKAMAK RESEARCH

4.1 The JET Tokamak

JET is a high current, high power tokamak with a low-Z first wall (Fig.4). The technical design specifications of JET have been achieved in all parameters and exceeded in several cases (Table I). The plasma current of 7MA in the limiter configuration and the current duration of up to 60s at 2MA are world records. Neutral beam (NB) injection has been brought up to full power (~21MW) and ion cyclotron resonance heating (ICRH) power has also been increased to ~22MW in the plasma. In combination, these systems have delivered 36MW to the plasma. JET can also operate with a magnetic limiter configuration, which is foreseen for ITER. In this configuration, the regime of higher energy confinement (H-mode) has been observed with confinement times exceeding twice those of the L-mode regime.

Table I

Parameter	Design Values	Achieved Values
Major Radius (R)	2.96m	2.5-3.4m
Minor Radius (Horizontal) (a)	1.25m	0.8-1.2m
Minor Radius (Vertical) (b)	2.10m	0.8-2.1m
Toroidal Field (B_T)	3.45T	3.45T
Plasma Current (I_p)	4.8MA	7.0MA
NB Power	20MW	21MW
ICRH Power	15MW	22MW

4.2 Performance in Deuterium Plasmas

Improved plasma purity was achieved in JET using beryllium as a first-wall material, by using strong gas-puffing and by sweeping the magnetic configuration over the target plates in

4.5 The New Phase of JET

Early in 1992, a New Phase began with the aim of establishing, in deuterium plasmas, reliable methods of plasma purity control under conditions relevant for the Next Step tokamak and to undertake preparations for the final phase of JET with deuterium-tritium plasmas. Specifically, the New Phase should demonstrate in an axisymmetric pumped divertor: control of impurities generated at the divertor targets; decrease of heat load on the targets; control of plasma density; an exhaust capability; and a realistic model of particle transport.

First results should be available in early-1994 and the Project will continue to end of 1996. Overall, the results should allow determination of the size and geometry needed to realise impurity control in a Next Step tokamak such as ITER; allow a choice of suitable plasma facing components; and demonstrate the operational domain for such a device.

5. TOWARDS A TOKAMAK REACTOR

5.1 Definition of a First Reactor

A first reactor (Fig.6) is likely to be a full ignition, high power device (1-2GW electrical), and will include: auxiliary heating; D-T fuelling; divertor with high power handling and low erosion; exhaust for impurities and helium ash; first wall with high resilience to 14MeV neutrons; hot blanket to breed tritium; and plasma control.

The parameters of a first reactor are defined by technology and physics predictions. The plasma minor radius, a~3m, must be about twice the thickness of the tritium breeding blanket and the plasma elongation, κ~2. A practical aspect ratio (R/a~2.5) sets the major radius, R~8-9m. Plasma physics requirements can be fulfilled with a toroidal magnetic field at the major radius of ≈6T. This defines a plasma current of ~25-30MA.

Simulations, based on modelling present tokamak experiments, show that ignition can be maintained in such a reactor, provided the exhaust and impurity control systems are effective. Steady ignition conditions can be achieved with a specific level of fuel "ash", but if the "ash" accumulates in the plasma centre, the ignition can be quenched. The "ash" must therefore be transported to the plasma edge, where it can be pumped away.

5.2 The Next Step: ITER

The overall aim of a Next Step tokamak is to demonstrate fusion as an energy source. Therefore, it should: demonstrate sustained high power operation (1-3GW thermal power for ~1/2 hour); study the ignition domain; study operating scenarios; define first wall technology; prove exhaust and fuelling requirements; provide a testbed for the study and validation of tritium breeding blanket modules in reactor conditions; achieve a cost/unit thermal output relevant to the establishment of fusion as a potential economic energy source; achieve a high level of safety and have minimum effect on the environment.

The International Thermonuclear Experimental Reactor (ITER) Project, started in 1987, represents the first step in worldwide collaboration between the EC, USA, the Russian Federation and Japan, under the auspices of the International Atomic Energy Agency. The main objective of ITER is to demonstrate the scientific and technological feasibility of fusion. The Definition and Conceptual Design Activities were completed in December 1990,and the four partners signed an agreement on the Engineering Design Activities in July 1992.

Currently, the ITER EDA is examining in detail whether these objectives could be achieved in a tokamak with plasma current up to 25MA, a toroidal magnetic field of ≈6T, major radius ≈7.75m, minor radius ≈2.8m, and elongation of 1.6. Impurities would be controlled actively by high density operation and a pumped divertor. The approach to ignition could utilise ICRH, while long pulse ignition (~1/2 hr) would be sustained in an X-point configuration at high power. With sustained ignition conditions, blanket modules could be tested under neutron fluxes of up to $2MWm^{-2}$. In addition, advanced divertors and concept development aimed at improved efficiency must be pursued.

5.3 A World Collaborative Programme towards a Reactor

ITER may be considered as the first component in a worldwide collaborative programme, to work more efficiently and to achieve effective solutions to the scientific and technological challenges presented by fusion research. The advantage of such a Programme must be to:

- reduce scientific and technological risks;
- allow flexibility to accommodate new concepts;
- provide a wider and more comprehensive database;
- offer flexibility in location and time scheduling;
- be more practical in industrial terms;

This programme should minimise risks and overall costs and should ensure efficient use of world resources. In support, National Programmes comparable in size would be needed. With concerted effort and determined international collaboration, world resources exist to proceed towards a Demonstration Reactor.

FURTHER SUGGESTED READING

Tokamaks by J. Wesson, Oxford Science Publications (1989);

Europe's Experiment in Fusion: The JET Joint Undertaking by E.N. Shaw, North Holland Publishers (1990)

Fusion: The Search for Endless Energy by R. Herman, Cambridge University Press (1990)

Tokamak Plasma: A Complex Physical System, by B.B. Kadomtsev, Adam Hilger Publishers (1993)

Fig. 1: Naturally occurring plasma influenced by magnetic fields near the surface of the Sun

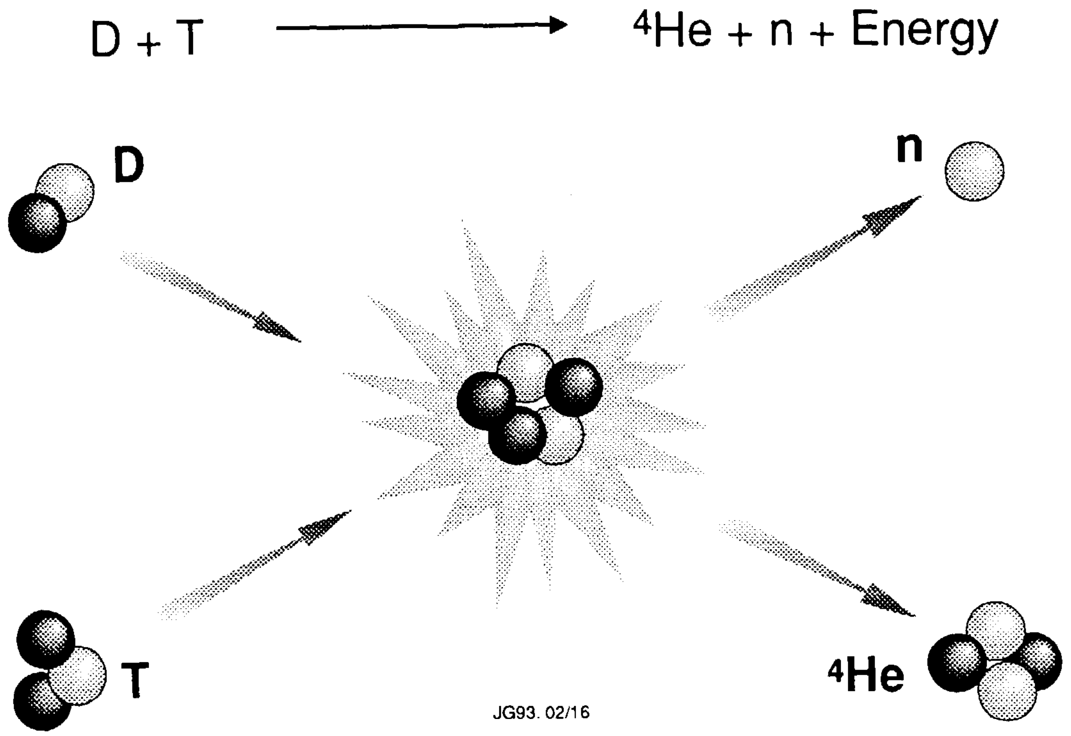

Fig.2: The Deuterium (D) - Tritium (T) fusion reaction

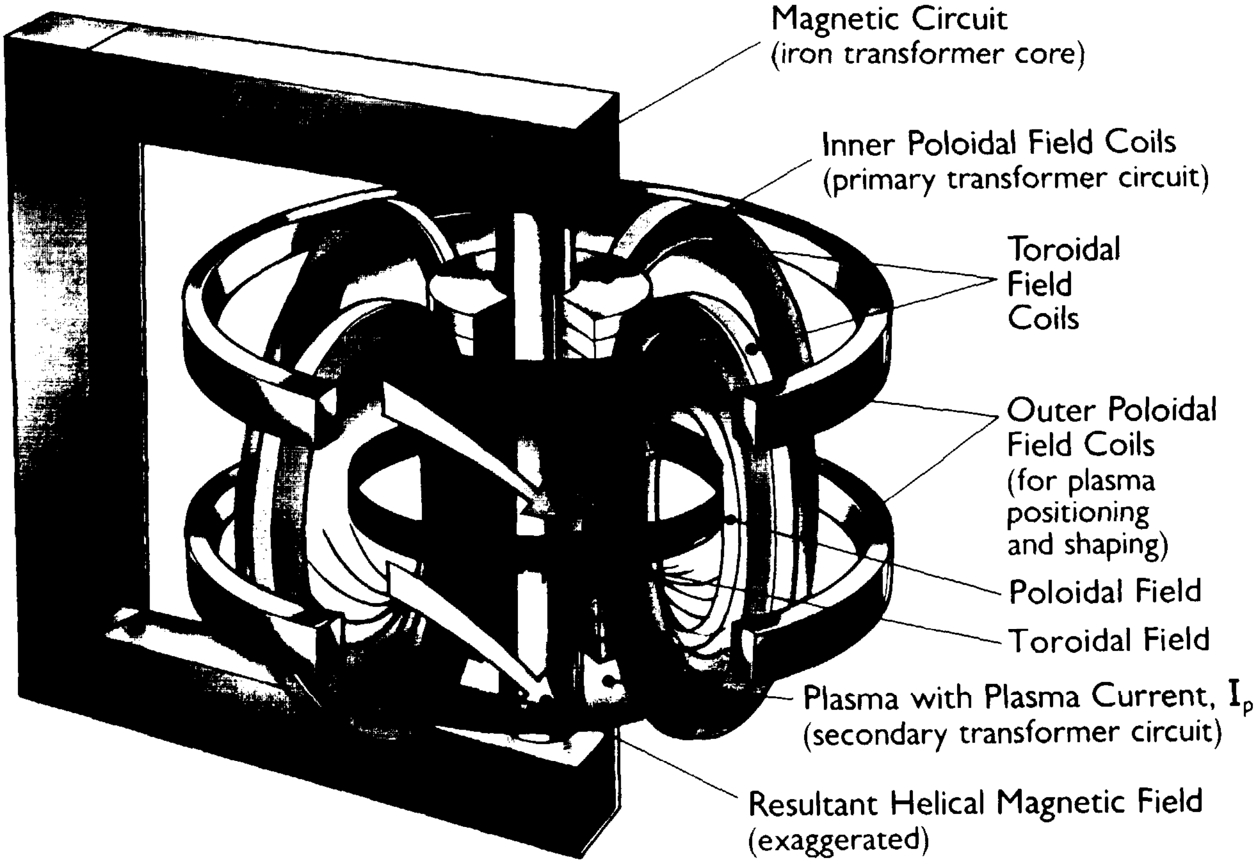

Fig.3: Schematic diagram of a Tokamak fusion device

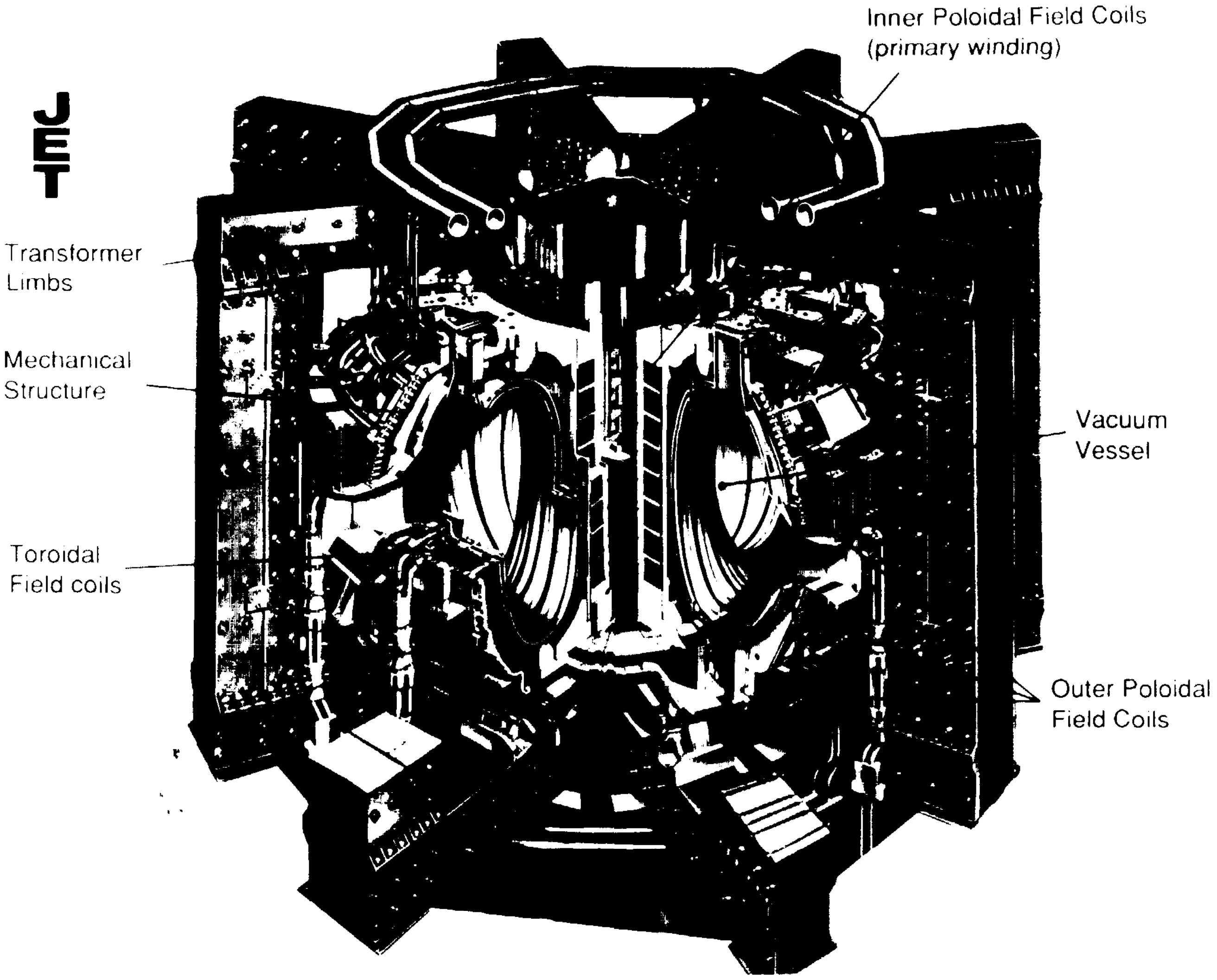

Fig.4: Diagram of the JET apparatus

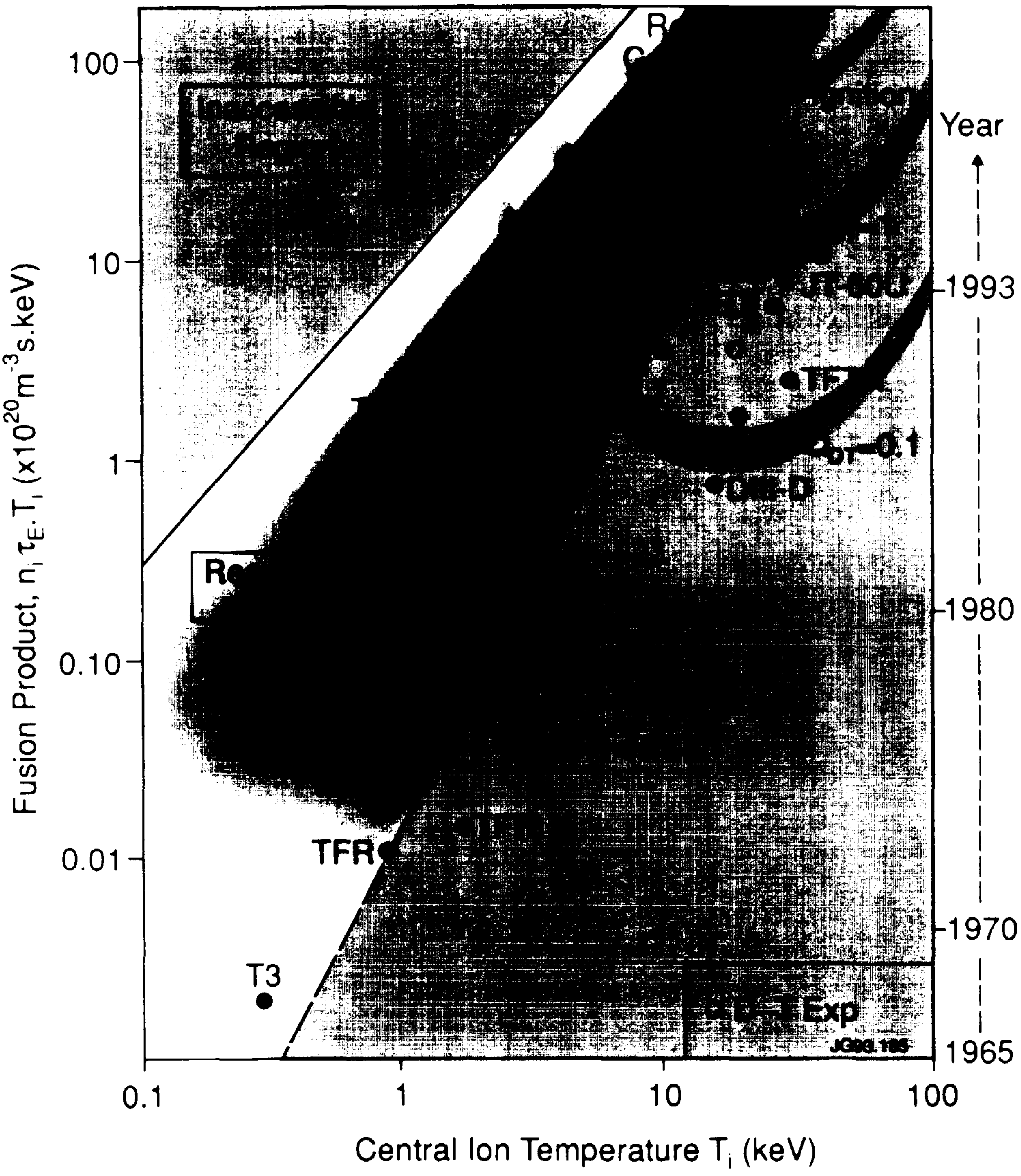

Fig.5: Fusion product ($n_D \tau_E T_i$) versus central ion temperature (T_i) for a number of machines worldwide during the period 1965-1993

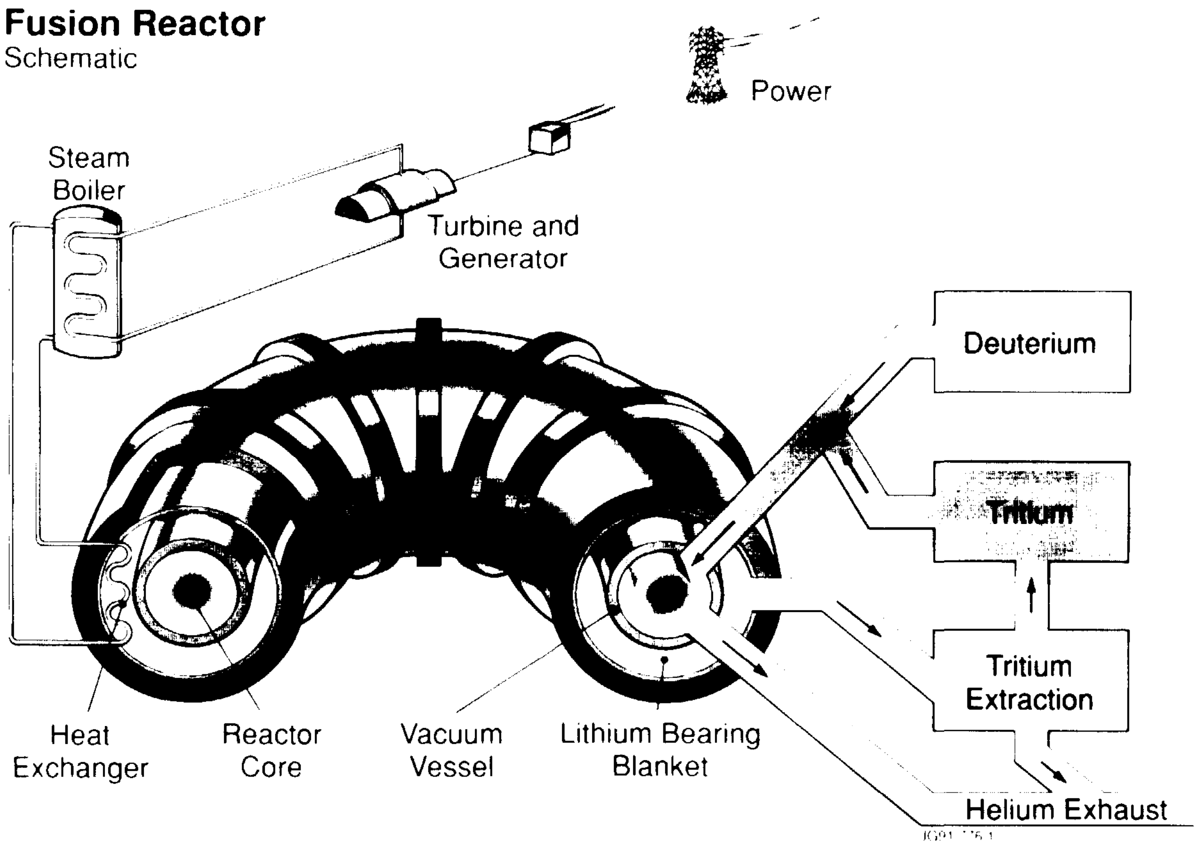

Fig.6: Schematic diagram showing the principles of a fusion reactor