A look at fusion reactor technology

Part I of a comprehensive overview by India's Dr. V. K. Rohatgi

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It is well known that controlled thermonuclear fusion promises an unlimited source of energy. Although the development of a thermonuclear fusion reactor has been of interest for more than three decades now, it is only recently that visible and convincing progress has been achieved in this field. This is mainly due to the rapid technological advances the world over. It is now certain that in the next century commercial fusion energy will become a reality.

Now that the physical principles of fusion energy are adequately understood, there are a number of schemes under way to produce fusion reactors on a laboratory scale. Fusion reactor design has become much more comprehensive and realistic during the last five years. The new breakthroughs at Los Alamos National Laboratory pointing toward compact and high density magnetic fusion have been summarized by Stevens (1984), and Coppi (1984) discusses the advanced fusion-burning core experiment proposed at the Massachusetts Institute of Technology (MIT). This article examines recent developments and efforts devoted to the design of fusion reactors. From this study, one can see that it is now possible to identify the engineering and technological requirements for the development of a thermonuclear power reactor. Several leading laboratories in the world have already initiated development programs along these lines. It is important to note that the technology required for fusion is also of interest to many other scientific and industrial applications.

Fusion energy development is the most difficult and important technological challenge of today. Concerted and committed efforts are required now to achieve this objective in the early part of the 21st century. This estimate assumes certain accelerated growth of technological evolution with successive step-by-step improvement in the course of time. However, if a real breakthrough occurs, this time scale may get compressed accordingly.

Principles of fusion energy

Although there are a number of reactions that can yield fusion energy, the most widely studied reaction for this purpose is deuterium (D) and tritium (T), where $D+T=n+{}^4He+17.6$ MeV (where n is a neutron, He is helium, and MeV is million electron volts). In this reaction, the neutron carries 14 MeV and the balance goes with the helium particle. Other reactions of interest are listed in **Table**

TABLE 1

Possible fuels for fusion energy

1. $D + T \rightarrow n + {}^4He + 17.6$ MeV
2. $D + D \rightarrow P + T + 3.25$ MeV
3. $D + D \rightarrow n + {}^3He + 4.0$ MeV
4. $D + {}^3He \rightarrow P + {}^4He + 18.3$ MeV
5. $P + {}^{11}B \rightarrow 3{}^4He + 8.7$ MeV
6. $P + {}^6Li \rightarrow {}^3He + {}^4He + 4.0$ MeV

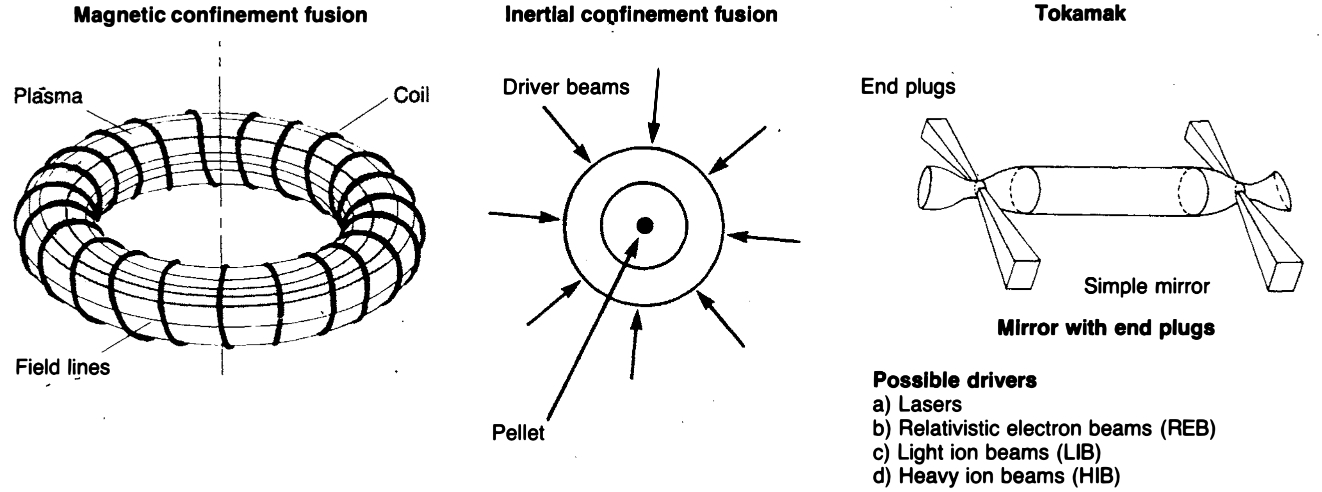
Breeder type fuels

7. $n + {}^6Li \rightarrow T + {}^4He$
8. $n + {}^7Li \rightarrow n + T + {}^4He$
9. $n + {}^7Li + {}^6Li \rightarrow 2T + 2{}^4He$

Multiplier type fuel

10. $n + {}^9Be + 2{}^6Li \rightarrow 2T + 4{}^4He$

FIGURE 1
Basic schematics of magnetic and inertial confinement systems



1. These reactions are considered less attractive at the present time because of their low yield and cross-sections for producing energy. However, with the advancement of technology and experience thus gained, these reactions can be used as fuels for specific gains in the future.

To be considered successful, a controlled thermonuclear reactor must perform three major tasks:

1) Heat fusion fuel above the ignition temperature of 10 keV and above, for DT fuel (keV is thousand electron volts).

2) Hold heated fuel long enough to release more fusion energy than the heat input. For a DT reaction, this requires $n \times \tau$ of the order of 3×10^{14} sec/cm^3, where n is the plasma density and τ is the confinement time. This is called the Lawson criterion. While scientific breakeven (that is, the fusion energy generated is equal to the energy invested in the plasma) can be demonstrated at somewhat lower values of $n\tau$, the ignition of the fusion reaction requires that this condition be fully satisfied.

3) Convert fusion energy released into electricity, or other direct applications. Requirements (1) and (2) must be satisfied simultaneously in a reactor before condition (3) is attempted.

There are basically two types of schemes being investigated to achieve a controlled thermonuclear fusion reaction: *magnetic* confinement and *inertial* confinement.

Tokamak, theta pinch, and magnetic mirrors are typical examples of magnetic confinement. **Figure 1** is a schematic of a tokamak and a mirror device with endplugs. In an inertial confinement system, the fuel pellet is irradiated by intense laser or particle beams. The reaction has to take place during a time shorter than the time taken by the pellet to disintegrate on its own due to ablation, evaporation, and decomposition. A schematic of this system is also shown in Figure 1.

Present status

Here is a list of some of the best results obtained so far that augur well for the development of fusion power reactors.

Magnetic confinement approach

Plasma temperature of 7.5 keV was reported in the PLT tokamak device at the Princeton Plasma Physics Laboratory in 1978.

Lawson criterion of $n\tau = 8 \times 10^{13}$ sec/cm^3 was achieved in the Alcator C tokamak at MIT in 1983.

The highest ion temperature of 2 to 3 keV was recorded in the TMX-U mirror device.

Lawrence Livermore National Laboratory improved the plasma confinement time from 10 milliseconds (ms) to more than 100 ms in the TMX-U tandem mirror device using endplugs in 1983. Significant improvement in plasma confinement was also demonstrated in the TARA tandem mirror device at MIT in 1984.

Inertial confinement approach

The world's largest carbon dioxide laser, Antares, with 30 kilojoules (kJ) per nanosecond (ns) went on-line at Los Alamos National Laboratory in 1984. Also on-line in 1985 was the Nova glass laser at LLNL with 100 kJ/1 ns, the largest glass laser in the world.

The highest yield of thermonuclear neutron flux of 3×10^{10} was reported with Lawrence Livermore's Shiva laser in a DT pellet.

TABLE 2
Large tokamak projects

Device	Location	Start of experiments	Major radius R (meters)	Minor radius a (meters)	Toroidal magnetic field B_t (tesla)	Current/T (megamps)	Auxiliary heating (megawatts)	Working gas	Special features
TFTR	Princeton, U.S.	December 1982	2.50	0.85	5.2	3.0	30[1]	H, D, D-T	Adiabatic compression
JET	Culham, U.K.	July 1983	2.96	1.25	3.5	5.0	40	H, D, D-T	D-shape ion cyclotron heating
JT-60	Tokai-mura, Japan	March 1985	3.00	0.95	4.5	2.7	30	H, D	Divertor lower hybrid heating
T-15	Moscow, U.S.S.R.	1986	2.40	0.70	5.0	2.3	15	H	Superconducting coils, electron cyclotron heating

[1]Not including compression

A better understanding of beam target interaction, approaching energy breakeven conditions, has been gained (IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, 1982).

Undoubtedly, the physics of fusion plasma remains to be further clarified. As a major step toward the demonstration of a successful fusion reactor, it is now necessary to establish, in a laboratory device, the scientific breakeven condition. That is to say, the device must be capable of producing fusion energy equal to the energy invested in the plasma. Breakeven conditions with ion temperatures approaching tens of keVs have been predicted in future mirror experiments such as the alternative configuration of TARA (known as MARS) and in the upgraded version of TMX-U (the MFTF-B). Likewise, according to Furth (1985b), the Tokamak Fusion Test Reactor (TFTR) is expected to achieve scientific breakeven conditions in 1986. Four large tokamaks worldwide have been designed with this specific objective (**Table 2**). The devices in the United Kingdom and the United States are already operating, and the device in Japan has just become operational (1985). The commissioning date of the Soviet tokamak, the T-15, is scheduled for 1986. In JET (UK) as well as TFTR (U.S.), operating parameters are being successively improved. The energy breakeven experiments will be attempted in these devices around 1986. The advances in tokamak development in the United States are summarized in

FIGURE 2
U.S. and European status in tokamak program

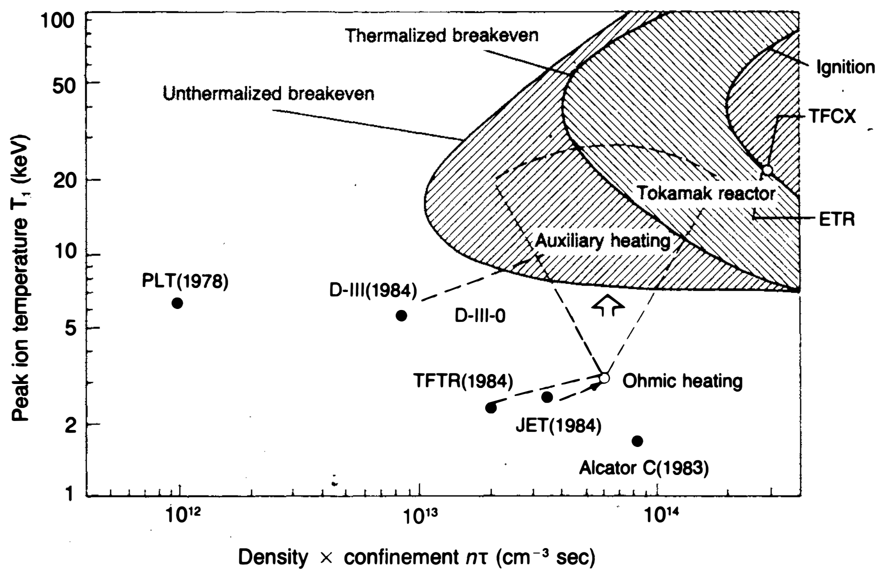


TABLE 3
Magnetic confined fusion reactor systems

	FED	FER	INTOR	CRFPR	TASKA	KARIN*
Configuration	Tokamak	Tokamak	Tokamak	Compact reversed field pinch	Tandem mirror	Moving ring reactor
Plasma temperature T (keV)	10	10	10	20	30	10
$n\tau$ (10^{20} m^{-3} sec)	2	2	2	0.6	0.5	—
First wall loading (MW m^{-2})	1.0	1.0	1.3	20	1.5	2.4
Thermal power (MW)	450	440	620	3,500	86	2,000

*New design concept of reactor combining the advantages of linear and torous configurations

Figure 2, which shows the achievement of Lawson confinement criteria versus the plasma ion temperature. As mentioned above, plasma temperature as high as 7.5 keV was obtained in the PLT device at Princeton in 1978. The highest Lawson criterion on $n\tau = 8 \times 10^{13}$ sec/cm^3 was achieved independently in 1983 in the Alcator C device at MIT. These results are very close to the desired values of temperatures and $n\tau$. The combination of these conditions will be attempted in the four large tokamaks (Table 2). Figure 2 also indicates the next steps after TFTR; namely, the Engineering Test Reactor (ETR) and the Tokamak Fusion Core demonstration Experiment (TFCX) which will be self-ignited. Experience on ETR and TFCX will permit the development of a fusion power reactor. **Figure 3** compares the U.S. and Japanese tokamak development program on the calendar year basis. It is interesting to note that the Japanese program is extended beyond JT-60 (equivalent to TFTR) up to a Demonstration Fusion Reactor (DFR). The intermediate stages of this program include the development of a Fusion Experimental Reactor (FER) and a prototype fusion reactor as well.

FIGURE 3
Comparison of U.S. and Japanese tokamak devices

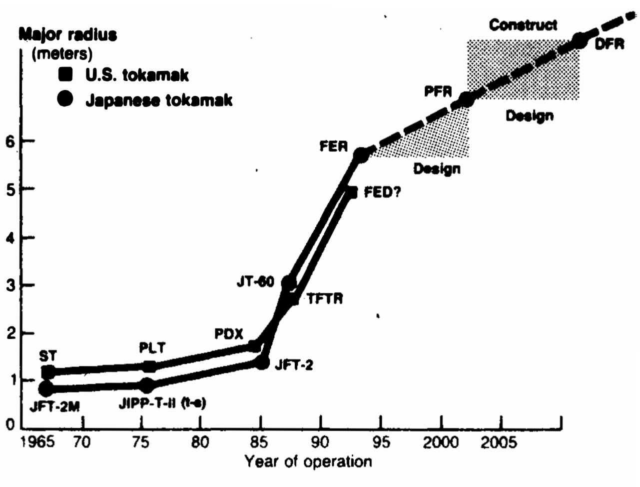
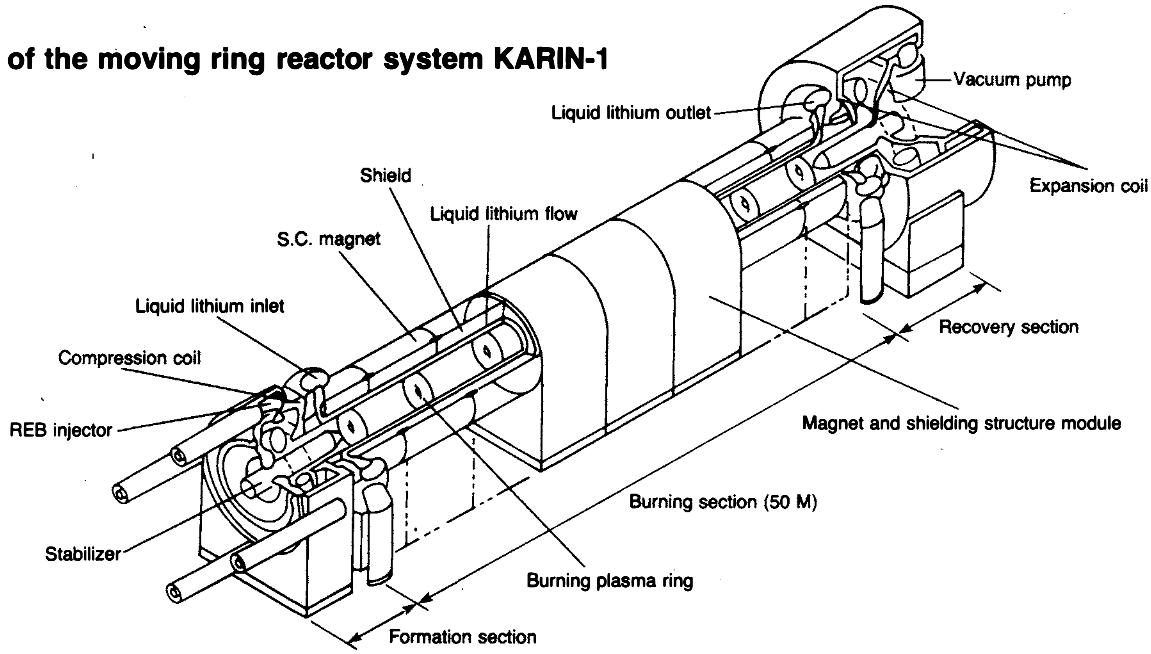


Table 3 lists some of the examples of reactor designs for magnetic confinement schemes. Other than the tokamak, there are reactor designs based on compact reversed field pinch, tandem mirror, and moving ring reactor concepts. These designs are representative of devices intended to establish the engineering details as well as power generation. Though not included here, there are similar ongoing programs in Western Europe aiming at developing comparable devices (Next European Tokamak or NET). In general, these are based on the smaller operating systems, and conventional designs are adopted in most cases except in the moving ring reactor.

The moving ring reactor, KARIN-1, has a unique approach that combines the advantages of both linear and toroidal configurations. The 2,000 megawatts-thermal (MWth) DT fusion reactor KARIN-1 has moving plasma rings that are produced by relativistic electron beam (REB) injection, heated by radial compression and conveyed in a linear cylindrical burning section by an annular liquid lithium flow outside a silicon carbide (SiC) first wall. The liquid lithium not only stabilizes the tilting motion of the rings, but also works as a tritium breeder and a coolant. The energies of ash accumulated rings are efficiently recovered in a subsequent section. The linear arrangement provides for easy maintenance of the system. The schematic layout of the reactor is shown in **Figure 4,** while the energy flow diagram for the same system is shown in **Figure 5.** As seen from this flow chart, REBs with an efficiency of 80% are used for the formation

FIGURE 4
Layout of the moving ring reactor system KARIN-1



of fusion plasma rings. The thermonuclear energy produced in the burning section is further multiplied in the blanket by a factor of 1.2. The system also envisages recovery of energy with efficiency of 70% in the downstream section of the reactor. In the first stage of this scheme, an overall efficiency of 30% has been estimated.

The schematic of an inertial confinement fusion reactor is illustrated in **Figure 6,** which identifies four major components: the driver pellet factory, reactor vessel including blanket systems, and the energy converter unit (Hoffman 1980). In the inertial confinement fusion scheme, maximum attention thus far has been given to the development of efficient drivers. Although initially lasers had been considered for this application, relativistic electron beams (REB) and high energy light and heavy ion beams have become more popular in recent years. Examples of a high-power laser for inertial confinement fusion work are summarized in **Table 4.** This table, which is only a partial list, includes examples of lasers being developed with different media such as glass, carbon dioxide, and iodine. There are many more facilities in operation as well as in development stages. Driving systems based on single and multiple beams are being devel-

FIGURE 5
Energy flow in the moving ring reactor system KARIN-1

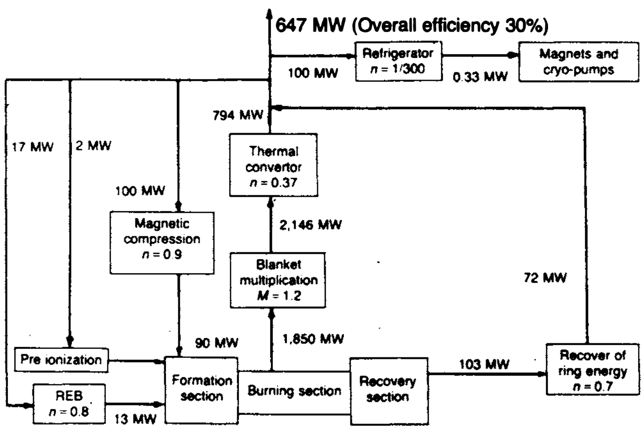
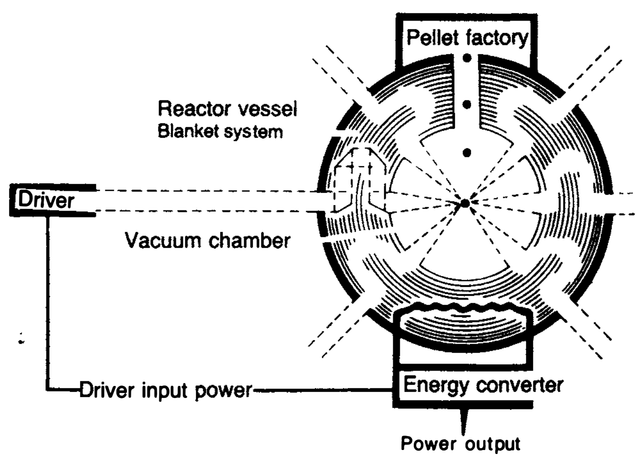


FIGURE 6
Inertial confinement fusion reactor



oped. Experiments are already in progress where high neutron yields have been produced with lasers impinging on fuel targets.

A selected list of particle beams being developed for driving fusion reactions is given in **Table 5.** This table includes examples of both electron as well as light ion beams. The work on heavy ion beams is relatively new and no operating facility has been reported to date. A heavy ion beam induction linear accelerator project has been started recently (1984) at Berkeley and is scheduled to begin target experiments in 1989. Another design is the HIBALL reactor concept in West Germany using a radio frequency linear accelerator with ring storage as the driver to give 10 billion electron volts (GeV), 5 MJ, 20 ns pulses of lead or bismuth ions with repetition frequency of 20 and target gain of 80. In the class of REB and light ion beams, two facilities, namely, PBFA II at Sandia National Laboratories in the United States and Angara V in the Soviet Union, are likely to be commissioned in 1986. In the case of PBFA II, physics studies of its high voltage (~30 MeV) lithium diode are planned to begin in 1985 in preparation for studies of the target-implosion hydrodynamics around 1988 at power levels of hundreds of terawatts/cm^2/radian^2. The status of REB Angara V is discussed by Aranchuk et al. (1982). These experiments are intended to demonstrate the scientific breakeven conditions for inertial confinement fusion.

TABLE 4

Examples of inertial confined fusion drivers

Lasers

Identification/ Location	Media	No. of Beams	Output power (TW)	Output energy (kJ)	Pulse length (nS)	Remarks
Shiva, LLNL, U.S.A	Glass	20	30	10	0.1-1.0	10^{10} neutrons
Nova I, LLNL, U.S.	Glass	10	100	100	0.1-3.0	Operational
Delfin, Lebedev Institute, U.S.S.R.	Glass	12	33	10	0.2-3.0	
Gekko XII, Japan	Glass	12	40	20	0.1-1.0	
Shanghai, China	Glass	6	10^{-4}	0.4	2.0	10^4 neutrons
Barc, India	Glass	4	1	1	1	Being developed
Antares I, LANL, U.S.A.	CO_2	24	40	40	1	10^{10} neutrons
Asterix III, West Germany	Iodine	1	1.1	0.4	0.35	

TABLE 5

Examples of inertial confined fusion drivers

Particle beams

Identification/ Location	Media	No. of Beams	Output power (TW)	Output energy (kJ)	Pulse length (nS)	Remarks
PBFA II, U.S.A.	Light ions	36	100	3,500	69	Commissioning date 1986
Angara V, U.S.S.R.	Electron	48	100	5,000	40-50	Commissioning date 1986
Ural, U.S.S.R.	Electron	1	0.01	1	100	
Reiden IV, Japan	Light ions	1	1	100	50	
Barc, India	Electron	1	0.1	5	50	Being developed
Sidnix, France	Electron	1	1	50	80	
Kalif, West Germany	Electron	1	1	55	45	