Fusion reactor technology

The third and final part of Dr. V. K. Rohatgi's overview of the state of fusion research and the requirements for reactor construction.

Dr. Rohatgi is head of the Plasma Physics Division at the Bhabha Atomic Research Center in Bombay, India. He also directs India's MHD (magnetohydrodynamics) program. Parts I and II discussed the present status of the two principal approaches to fusion power, magnetic confinement and inertial confinement, and began to consider the technology requirements for building a fusion reactor; that analysis is concluded here. Readers wishing to consult Dr. Rohatgi's extensive bibliography may obtain a copy from EIR.

Construction materials

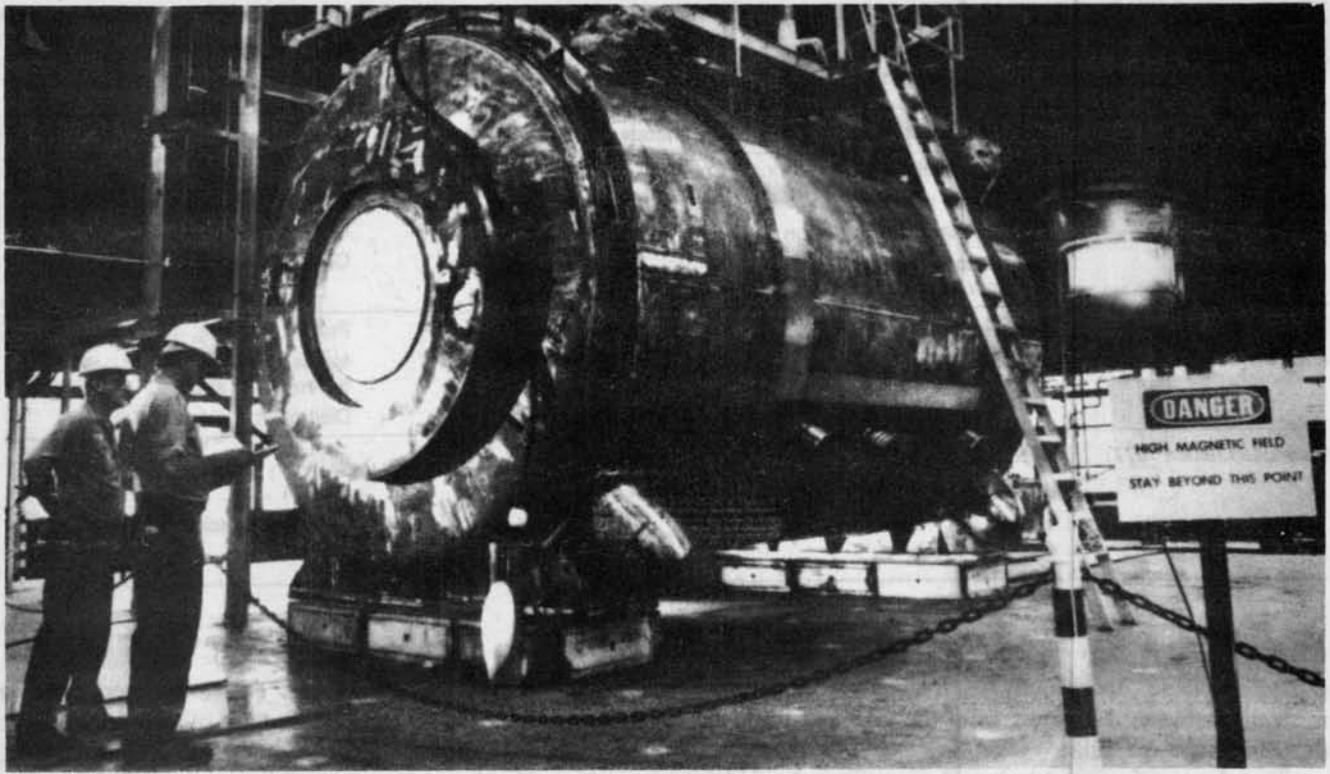
Major efforts in recent years have been focused on specification, selection, development, and fabrication of suitable materials for fusion reactors (Jarvis 1982). Both metallic and nonmetallic structures show sensitivity to a fusion environment. Accordingly, both the classes of material structure are receiving attention. At Los Alamos National Laboratory "All Ceramic" (Clinard 1979; Clinard and Huxley 1981; Clinard et al. 1983; Dike and Haberstiah 1979; and Hauth et al. 1979) and "All Metals" (Dike and Downing 1981) designs for the tokamak have been evolved. Study of plasma-boundary interaction is important, both from the point of view of creating and sustaining fusion-grade plasma, and also from the point of view of the mechanical integrity and reliable long-life operation of the vessel.

In this connection, physical and chemical erosion of reactor wall is a critical problem area in chamber design. The plasma interactions with the reactor walls of the inertial confinement fusion cavity have been analyzed by Bohachevsky (1981) and his group at Los Alamos National Laboratory. The chamber construction material also deserves consideration from the point of design of the vacuum system, as is discussed later.

The progress of fusion material research during the last few years is shown in **Table 8** (Kulcinski 1983). This table divides metallic, nonmetallic, and environmental materials into three categories. The assessment is qualitative, in terms of considerable progress, little progress, and new ideas since 1977. The map of material design and analysis program in relation to the microstructural properties of the material, as drawn up by the University of Tokyo Group (Ishino and Iwata 1983), is reproduced in **Figure 10.** This diagram clearly brings out the interrelationship between the microstructure, physical properties, and performance evaluation of materials.

It is estimated that the peak fluxes of heat and radiation will be orders of magnitude higher, in the case of inertial confinement fusion reactors as opposed to magnetic confinement fusion reactors of comparable power rating. Test facilities are being created to study the material behavior under simulated conditions. **Figure 11** shows one such facility developed jointly by Westinghouse and Argonne National Laboratory in the United States, to test fusion reactor first wall components (Varljen et al. 1983). This facility uses high-power electron beams as a source of heat to study the thermal-mechanical and thermal-hydraulic response of various concepts being considered for the first wall design. The response of metals with electron-beam heat sources has been analyzed by Vijayan and Rohatgi (1984a, 1984b).

Plans are under way to study the neutronics and radiation effects in first wall and blanket designs. The studies so far indicate that vanadium-alloyed steel is better than other alloys, in terms of activity considerations and disposal problems (Volger et al. 1983) and resistance to radiation (Bloom et al. 1982). Moreover, simulation studies indicate that ceramic structures can withstand high neutron fluxes ($\sim 10^{22}$/



The Super-Magnet, a superconducting dipole magnet from the Argonne National Laboratory in the United States, built for use in MHD power generators. These generators may solve the problem of supplying the high-voltage power required for fusion reactors.

cm^2) without undergoing serious damage and changes in their properties (Porter 1982). Studies have been made with solid as well as liquid lithium breeders. In view of potential fire and explosion hazards, solid breeders are preferred to liquid breeders (Cooper 1983). Solid breeders in the form of lithium oxides are found safer, while they can also provide necessary structural insulation (Hollenberg et al. 1984; Vogler et al. 1983). Using neutron multiplier-based solid breeders like Li_2ZrO_3, the advantage of tritium breeding can be enhanced through ^6Li reaction.

Superconducting technology

Superconducting material and technology development have attracted significant attention during the last few years (Haubenreich et al. 1982). The development of superconducting material, cryogenic system, and testing of large magnets with low risk and high reliability is still one of the major areas demanding concentrated efforts. The requirements of superconducting-magnet design should satisfy unconditional stability conditions (Cooper 1983). Apart from general studies in the development of superconducting magnet technology, specific problems related to the magnetic coils for tokamak have been analyzed (Komarek 1980). It is concluded that from the point of view of total reactor systems, superconducting-magnet technology forms the weakest link in the chain (Shimamoto et al. 1983; Tsuji et al. 1981). Accelerated efforts are therefore recommended in order to bring this technology to an acceptable level. The design complexities of this single component weigh heavily in favor of mirror configuration for fusion reactor in place of tokamak.

High-voltage power systems

The electrical power supplies in large fusion experiments and reactors have to serve many difficult as well as varied tasks. For instance, in magnetic confinement fusion reactor power, supplies are required for generating and heating the plasma, creation of magnetic field for confinement, stability, and position control of plasma. Depending on the function, these supplies vary in peak power and duration of the pulse. The characteristics of these power supplies must match the physical behavior of the plasma. Also important are the rise time and synchronization of operation of different power supplies. Keeping in view the perspective of large fusion experiments and possible reactor designs, power supplies in the range of Megajoule to Gigajoule for durations of a few nanoseconds to seconds will be required. In the case of inertial confinement fusion, the peak power of several orders higher is envisaged. The short pulse durations are of particular interest for inertial confinement fusion reactor application. Such loads for normal power grids are rather unusual

TABLE 8

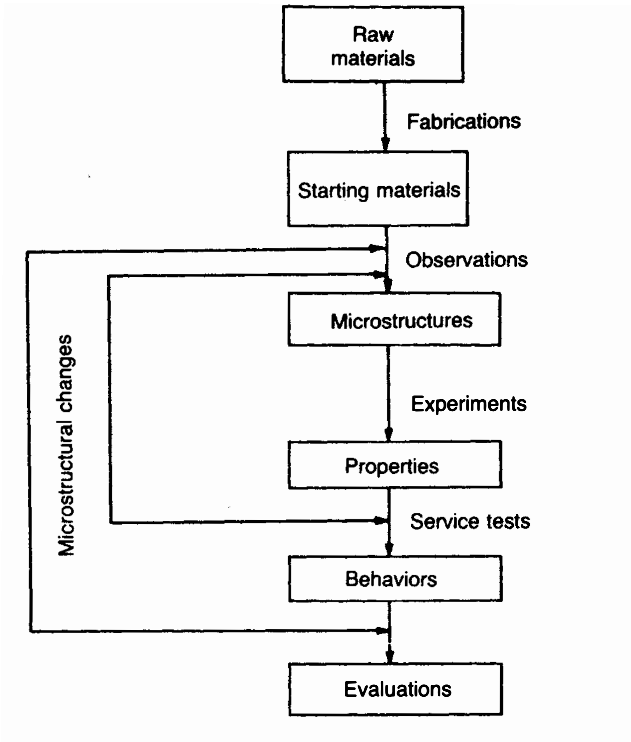
Status of fusion material research

	Metallic structures	Nonmetals plus coolants	Reactor environment
Considerable progress	FW vaporization/melting FW lifetime analysis Divertor plate, limiter design Low temperature, high He neutron data	Chemical sputtering-C High heat flux coatings	FMIT construction started Inertial confinement fusion cavity gas reradiation Charge X-change sputtering
Little progress	Pulsed neutron damage Permanent FW	Low T_2 inv.-solid breeders High temperature *n* damage-C	Pulsed *n* source Inertial confinement fusion target spectra Disruption characteristics
New ideas (since 1977)	Martensitic alloys Rapidly cooled alloys	$Pb_{83}Li_{17}$ breeder/coolant SiC import units	INTOR TASKA Steady state tokamak

and unacceptable. Accordingly, the total power requirement is shared between the power from the grid and from the independent power racks.

FIGURE 10

Materials design and analysis with respect to the position of microstructural design



Thus far, condenser banks have been commonly used as primary energy storage devices. The stored energy is then transported to the actual load through a suitable intermediate system, depending on the load characteristics. Only recently, governed by the requirements of the advanced fusion experiments, other energy-storage systems have been investigated. **Table 9** lists the performance characteristics of different energy-storage systems (Bertolini 1980). Because of the demand on high reliability, the power supplies have been developed with conventional equipment. This tends to make physical sizes big and also limits the applicability to a given task. The cost of power supplies can be a significant fraction of the project cost. For example, in the case of JET (the large English tokamak), power supplies take up about 17% of the budget and 35% of the hardware. This trend will continue, unless major design changes in the equipment take place.

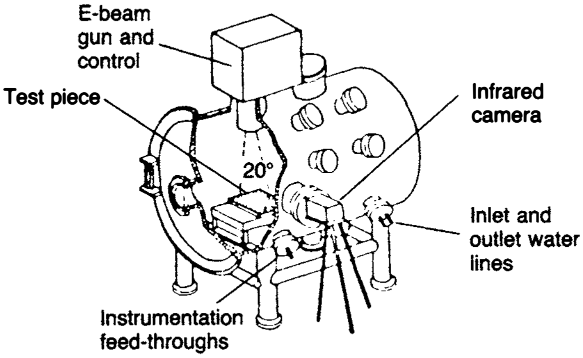
One possibility is the use of superconducting material, both in the test equipment as well as in the energy-storage and handling systems. While small tokamaks are already operating with superconducting magnet coils (SMC), the design of SMC for large tokamaks has also received considerable attention. This will drastically reduce the power requirements of the magnet coils. Likewise, inductive energy-storage system, rotating machinery, and energy-transfer equipment with superconducting coils could also lead to compact designs with higher efficiencies.

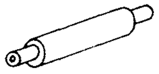
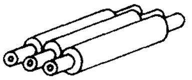
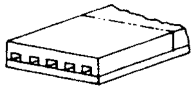
Homopolar and pulse MHD generators offer alternatives to conductive and inductive pulse energy sources. A homopolar generator is a device in which a DC magnetic field exists along the axis of a cylinder. The homopolar machine driven by a motor/gas turbine generator, induces voltage in a radial direction which is connected to the load through brush contacts. A homopolar device can serve both for the motor as well as the generator. Besides, since it is a DC machine, no rectifiers are required. Machines in the range 50-2,000 MJ

FIGURE 11

Electron beam material testing trolly

(power on test piece up to 100 watts/cm² in vacuum)



Test piece	Description
	Single stainless steel tube
	Three tubes facsimile of a stainless steel heat rejection panel
	Facsimile of a stainless steel flat plate heat rejection panel
	Full-scale graphite armor tile attached to a water-cooled stainless steel plate via a mechanical dovetail joint

Initial first wall test pieces derived from current FED design concepts

have been developed. One such machine, producing 500 MJ for 0.5 seconds, giving a current of 1.6 million amperes, has been built and tested at the Australian National University, Canberra. With rugged structure, ratings of the machine can be increased. The expected efficiencies of around 80% have been projected (Bertolini 1980).

MHD power generators work on the principle of the Faraday Law of Induction, in which a conducting fluid (plasma) flows across a DC magnetic field and the induced voltage is directly connected to the load through suitable electrodes (Rohatgi and Venkatramani 1984). Linear as well as cylindrical configurations have been developed for continuous and pulse-power generation. In general, any type of heat source such as the combustion products of solid, liquid, and gaseous fuels (including nuclear and solar energy) can drive an MHD generator. Typically, plasma temperatures of 2,000-3,000°C and flow velocities of 500-2,000 m/sec are used for combustion-driven MHD generators. Pulse MHD generators up to 100 MW(e) and of a millisecond to a minute duration, are already in use in terrestrial and space applications. The simplicity and reliability of these devices have attracted special interest in defense and aerospace industries. Long-duration generators are being developed for central power stations. Already 20 MW(e) for several hours have been generated continuously at the U-25 MHD installation in Moscow. The first commercial MHD/steam plant of 1,000 MW(th) is under construction near Moscow, and the conversion efficiencies of this power station using natural gas has been estimated to be around 50%.

In short, it is concluded that the high-voltage power supply for large fusion experiments and subsequently for power reactors will continue to claim a significant fraction of the budget and efforts. Accordingly, concentrated efforts should be devoted to the development of high-efficiency, compact, and reliable power supplies (Ron 1982). While reliability could be achieved using conventional designs and components, there is a case for more innovative approach and designs based on advanced technology, materials, and components.

Plasma heating systems

Auxiliary heating of plasma to reaction temperatures is a must in magnetic confinement fusion reactors. Neutral, charged particles and radio-frequency beams have been attempted for this purpose. The best results in a tokamak were obtained with a neutral beam in 1978 (PLT 1978). Radio-frequency heating of plasma has also been found attractive (Porkolab 1977). At the same time, it is difficult to eliminate particle (electron and ion) beams at this stage (Arzhannikov et al. 1978; Paithankar and Rohatgi 1979; and Krakowski 1978). In the Tokamak Fusion Test Reactor (TFTR) at Princeton, neutral-beam heating has been selected, whereas

TABLE 9

Characteristics of energy storage systems

	Performance	
System	Joule/m³	Watt/m³
Capacitors	10^4-10^5	10^9-10^{10}
Inductors	10^7	10^7-10^8
Rotating machines	10^7-10^8	10^8
Batteries	10^8-10^8	10^6
Explosives	10^{10}	10^{15}

other similar devices contemplate using radio-frequency along with neutral-beam heating for experimental purposes. Radio-frequency power can be pumped into the plasma through electrons as well as ions.

Among the various modes of radio-frequency coupling to plasma, the ion cyclotron resonance and lower hybrid frequencies are more attractive. Encouraging results have been obtained in laboratory-scale experiments. Consequently, high power sources over a wide range of frequencies (approximately 0.1 kHz to 200 GHz) are of interest for suitable plasma heating. All the available sources for auxiliary heating today fall short of the requirements. For instance, neutral beams in the range of 100-1,000 kW have been developed at the University of California and Oak Ridge National Laboratory in the United States. These devices have to be scaled up in the range of 10-100 MW for reactor applications. Likewise, pulse radio-frequency sources in the range of a few megawatts are presently being used in experiments, whereas the requirement for the reactor will be in the range of 10-100 MW. Recent developments in relativistic electron beam and free electron laser (FEL) offer attractive possibilities in developing high power variable frequency radio-frequency sources, and also for direct coupling of free electron laser for plasma heating (Schwarzchild 1985).

Since they are in the experimental stages, it is not clear which of these techniques will be adopted in the final design. A combination of these may also be adopted at that stage. In any event, technologies of each of these schemes will have to be scaled up at least several fold from the present level. The final selection may also depend on the availability of the essential technology.

Laser, relativistic electron beam, and light ion beam find a place in the inertial confinement fusion reactor as well as in the magnetic confinement fusion reactor. Thus far, the emphasis in the development of these drivers has been for the pellet heating. The use of the relativistic electron beams/light ion beams for magnetic confinement fusion reactors is relatively recent. It is observed that such beams are particularly suited for linear devices (Paithankar and Rohatgi 1979; and Miller 1975), at the same time that means of injecting them into toroidal systems are being studied actively in several laboratories (Lockner and Kusse 1978).

Both from the scientific as well as from the technological point of view, particle beams offer definite advantage for plasma heating in fusion reactors. However, the beam drivers developed for the inertial confinement fusion reactor cannot be directly adopted for magnetic confinement fusion reactor applications. As mentioned earlier, the inertial confinement fusion reactor requires a compressed pulse of a few-nanosecond-duration with high-peak power and a certain repetitive rate governed by the reactor design.

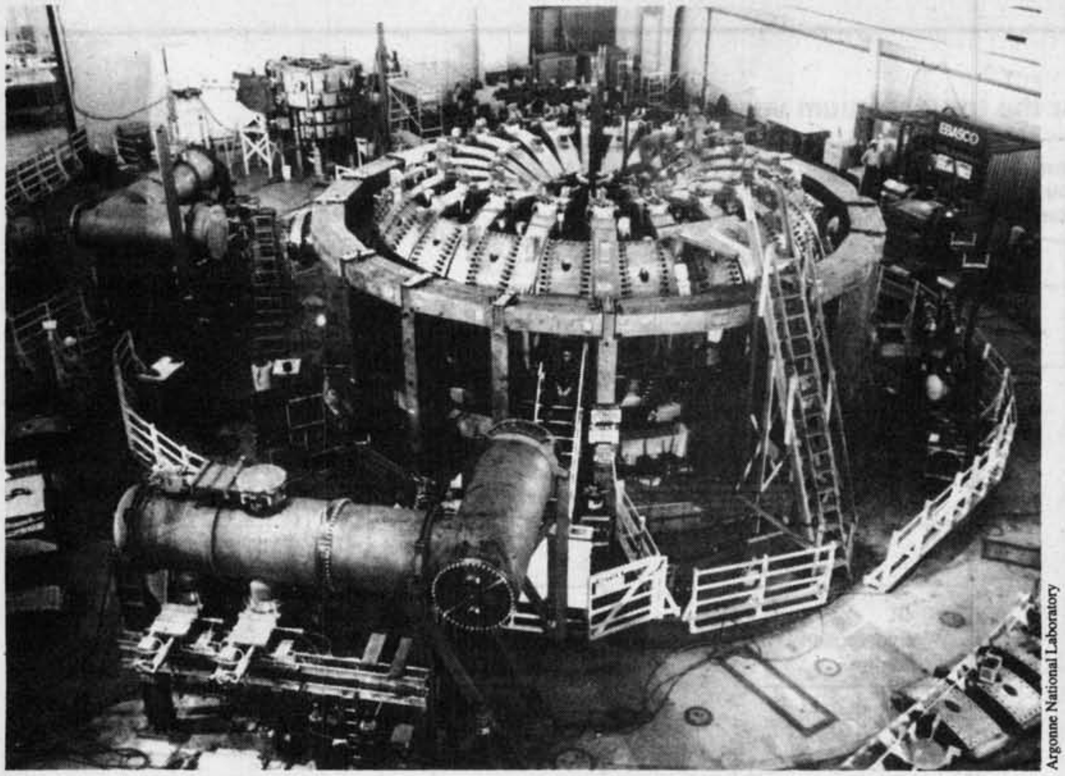
In the case of the magnetic confinement fusion reactor, on the other hand, one would need pulses of longer duration (maybe on the order of seconds). Also highly focused beams may not be necessary for the optimum absorption of energy in plasma heating.

One of the major problems in the development of the inertial confinement fusion reactor is related to the high-efficiency driver which can be focused onto the target (Monsler et al. 1981). Thus the beam transport (especially for relativistic electron beams and light ion beams) has been one of the problem areas in this context (Wallis et al. 1975). An intense burst of particles must travel through gaseous or metal vapor media in the reactor chamber. This results in considerable energy loss and defocusing of the beam reaching the target. Several schemes based on (a) self-focusing of the beam, (b) passage through pre-ionized low-density cold plasma, including plasmas produced by exploding wires (Goldstein et al. 1977; Vijayan and Rohatgi 1985), and (c) guiding magnetic fields, are being considered for this purpose.

The problem of beam transport in low pressure gases and in the absence of magnetic-guide field has been analyzed by several investigators (Chodorow and Ertiza 1976; Iyyengar and Rohatgi 1983, 1985; and Ono 1979). Preliminary investigations with laboratory-scale experiments indicate that for a given energy beam, there exists a narrow window in the pressure range through which beams can be transported with high efficiency and minimum defocusing (Rohatgi et al. 1984). While passing through the media, part of the beam energy is used in creating necessary ionization in the gas, which helps neutralize the space charge. This permits the beam transport with higher efficiencies (~70%), and obviates the need for external magnetic fields or pre-ionization. Also, observations indicate that operation of a relativistic electron beam diode in the same pressure range reduces the pulse width with the increase in the beam current (Mittal et al. 1981). These results are significant in simplifying the reactor designs, and merit further investigations to establish their effectiveness at reactor scales.

Vacuum and ash handling systems

The design of vacuum systems for a fusion reactor is an interesting problem. The plasma behavior strongly influences the design considerations of the vacuum system (Miyahara 1983). For instance, the vacuum system in the magnetic confinement fusion reactor is required to maintain a particle balance between fueling particle, high-energy neutral beams (NBI) used for auxiliary heating of plasma, neutron flux, the products of combustion, and the impurities emanating from the reactor vessel (Post et al. 1978). The sources and influx of impurities in the case of Alcator C have been studied by Rice at al. (1984). The design of vacuum system will be altered if radio-frequency heating technique is selected in place of high-energy neutral beam. As the unburnt fuel (DT) passes through the vacuum system, along with helium and impurities, the system must be capable of differentially pumping various constituents in the reactor chamber. Impurities in the reactor can also enter along with fuel and neutral beam injection. Care has to be exercised to prevent the impurities from entering through this route. The plasma reaction



Argonne National Laboratory

Princeton University's Tokamak Fusion Test Reactor, shown here under construction. On Aug. 7, 1986, scientists achieved a temperature of 200 million degrees Celsius in the TFTR—the highest temperature ever recorded in a laboratory. This temperature is in the range required for a fusion reactor, and, according to the U.S. Department of Energy, places the U.S. fusion program on target to achieve a practical fusion reactor within 15 years. The goal for the coming year is energy break-even, which means that the release of energy from the fusion process exceeds the amount of energy needed to generate the process.

products have to be effectively exhausted to avoid dilution of the fuel in the subsequent firing. In general, fuel can be reprocessed and recycled along with make-up fuel for the loss.

Thus, fuel particles recirculate through the vacuum and injection systems, while impurities and ashes are pumped using cryosurface. It is desirable that a large fraction of fuel particles recirculate between plasma and the walls of the reactor vessel, in order to reduce the tritium load through the vacuum system. The release of unburnt fuel from the reactor walls, in turn, is accompanied with the release of impurities which originate from the reactor walls. The whole phenomenon is sensitive to the plasma edge temperature which governs the unloading of fuel, as well as impurities from the walls of the chamber. Clearer understanding of the physics of this phenomena is required to evolve suitable designs for vacuum and ash handling systems. In the final stages, the blanket effect will also have to be included in the design consideration.

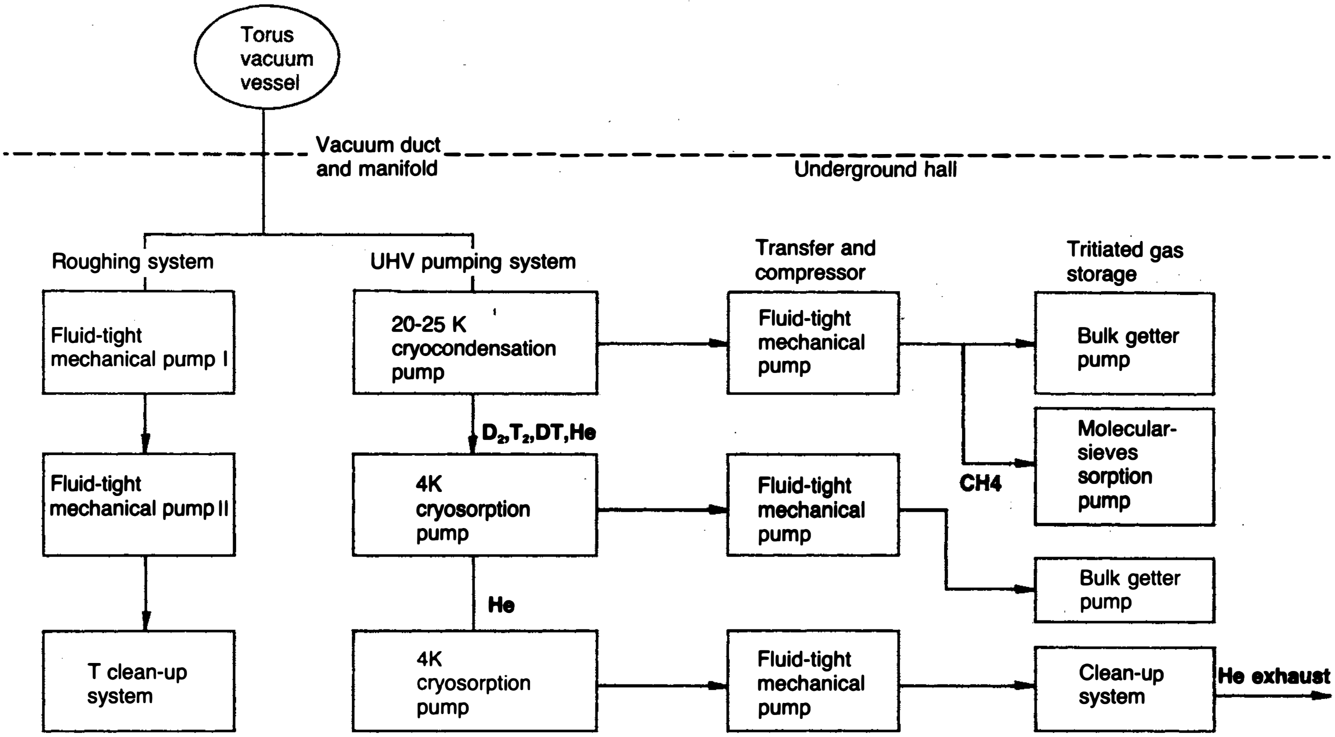
The role of the main pumping system is to achieve an ultimate vacuum of the order of 10^{-8} to 10^{-9} Torr and to separate the pumped gases into three fractions of helium gas, hydrogen isotope D_2, T_2 and DT, and impurities like CO, CO_2, DTO, CT_4, and so forth. **Figure 12** shows a typical scheme of a vacuum system for a power reactor (Miyahara 1983). By separation of gases, handling of tritium becomes easy. Both charcoal as well as metallic cryopanels have been considered for this purpose in the UHV pumping system. The impurity gases from the torus walls or normal DT discharges are pumped at 20 to 25 K cryocondensation, whereas helium and hydrogen isotopes pass through the second phase at 4°K. As this stage, hydrogen isotopes are separated due to their different condensation temperatures, while helium goes to the next 4°K cryopump with charcoal absorbent. Each stage is backed up with fluid-tight mechanical pumps and a final stage of the bulk getter or molecular sieve beds. Normally, two sets of pumping systems are incorporated—one for normal operation of pumping the torus and the other for regeneration experiment at a later stage.

The requirements of the vacuum system are not so strict in the case of inertial confinement fusion reactors, as compared to the magnetic confinement fusion reactors (Yamanaka 1983). In this case, the condition of vacuum is determined by the transmittance of the driver (laser, electron/ion beams) and the lifetime of the cryogenic fuel pellet. The evacuation of the target chamber is done by the lithium flow, whereas the gases and the products of implosion, including tritium, are done by the auxiliary pumping system. The entire system has to be free from impurities to a high degree. Normally, this is achieved by proper selection of reactor material followed by provisions of discharge cleaning.

A conceptual design of a laser-induced inertial confinement fusion reactor, SENRI-1, has been developed at the Institute of Laser Engineering, Osaka University, Japan (Ya-

FIGURE 12

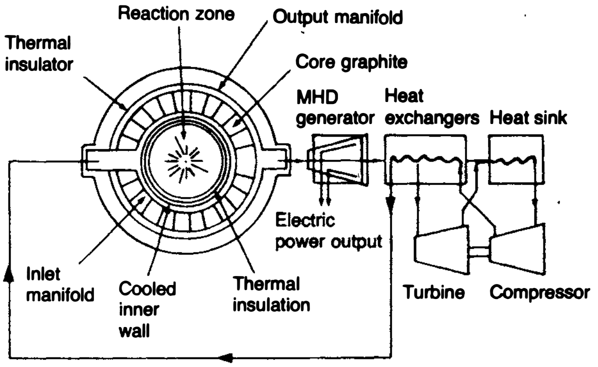
Pumping system for the torus vacuum vessel of the tokamak



manaka et al. 1983). In this design, the operating temperature of the lithium blanket is around 750°K, while the pressure is 10^{-3} Torr. The liquid lithium covers the surface of the reactor vessel and can act as a cryogenic pump which demands no extra large pumping system. Depending on the transmittance of the driver used, a working pressure of around 10 Torr may be adequate.

FIGURE 13

MHD system coupled to a fusion reactor



As mentioned earlier, the particle beam transport through gaseous/metal vapor media become important from this point of view. For this purpose, the design of vacuum system components and special construction materials have to be developed. The importance of selection of the construction material for the reactor vessel, which has to withstand high heat, radiation, and particle fluxes, is a different task. Preference should be given to materials of low outgasing rates both for the reactor chamber as well as for the rest of the manifold. Materials resulting in high impurities are also damaging from the point of energy confinement since they cause significant radiation loss. Other important components in the vessel are antenna for radio-frequency injection of power for plasma heating and sensing elements for plasma control and positioning. Because of the tritium pumping, oil-free mechanical pumps, reliable gaskets of large size, and gate valves must be developed for this application.

Utilization of heat of the reaction

Thus far, most attention has been focused on the development of science and technology required for achieving the thermonuclear reaction in a controlled fashion. The technological requirements listed above address this aspect only. Relatively little work has been done on the utilization of the energy released from the fusion reaction.

In general, it is envisaged that the energy associated with the neutron (14 MeV in a DT reaction) will be used for generating heat, tritium breeding, and interacting with fertile material in the blanket, which then can be converted into electrical power through the well-established steam cycle. In this case, a special heat exchanger suitable for the local environment may be developed which will eventually drive a steam turbine as in the case of conventional nuclear cycles. The plant efficiencies in most cases have been estimated on this basis which are of the order of 30%. This approach does not call for major technological development.

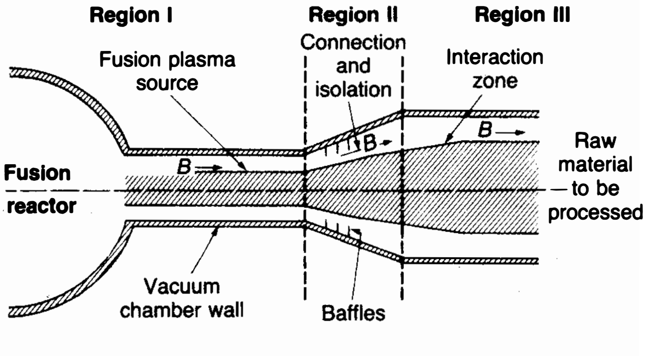
However, with the present state of the art of advanced technology, it is possible to conceive schemes which will result in higher conversion efficiencies. In particular, a binary cycle can yield conversion efficiencies in the range of 50-60%, compared to 40% with the conventional steam cycle. Also, for the optimum utilization of a high-energy-density source, one should consider a fusion reactor for cogeneration, rather than only for electrical power generation.

The MHD generator offers an attractive possibility and is ideally suited for this purpose (Rohatgi and Venkatramani 1984). A closed-cycle MHD generator operating in nonequilibrium plasma mode can be easily coupled, through a heat exchanger, to a fusion reactor. Assuming an operating temperature of 2,800°K, the overall conversion efficiencies of the MHD steam cycle has been estimated to be on the order of 60%. Further, it may be possible to extend this limit up to 80% with advanced technology. A conceptual scheme of MHD/steam binary cycle suitable for a fusion reactor is shown in **Figure 13** (Kautrovitz and Rosa 1975). Similar schemes have also been developed for inertial confinement fusion reactors. The MHD technology for this application is well established.

FIGURE 14

The fusion torch

This torch would permit an advanced utilization of energy to produce finished materials like iron and steel in one-step processing of raw materials.



Alternatively, the MHD generator can be driven by the charged particles produced in a fusion reactor. In this case, a stream of charged particles will pass through a transverse magnetic field of the MHD generator. This concept will be ideally suited when the following reactions are used in a fusion reactor:

$$P + {}^{11}B \rightarrow 3\,{}^{4}He + 8.7\text{ MeV}$$
$$P + {}^{6}Li \rightarrow {}^{3}He + {}^{4}He + 4.0\text{ MeV}$$

Heat and radiation generated in a fusion reactor can also be used for other industrial applications. Typical applications include large-scale material processing, and agricultural and medical sterilization. A novel concept proposed for this purpose is to develop fusion torches utilizing the energy available with the charged particles (FEFN 1977). The beam of charged particles is focused with a magnetic field on to the material to be processed, as depicted in **Figure 14.** This arrangement will permit the processing of finished items in a simple step.

Conclusions

In conclusion, it is seen that the first order of physics for fusion energy has been adequately understood. Now it is possible to take up conceptual designs for fusion reactors. Both magnetic confinement fusion and inertial confinement fusion schemes are available to choose from. The present designs are based on established techniques, but require further development. As the same time, this does not preclude introduction of new ideas from consideration toward the end objective. The extent to which the technology needs advancement has been identified. Looking at the quantum of work and the spectrum of technology required for fusion energy, it may indeed appear to be an arduous task. However, it should not be forgotten that the rewards of these efforts will be far-reaching. Even the partially developed technology of fusion energy of today has started paying rich dividends, let alone the fully developed technology which promises to be the ultimate answer to the energy requirement of the generations to come. Concentrated and planned efforts, with full commitment, are required to achieve the goal of fusion energy. With the current tempo of work in the development of fusion energy in the world, it is possible to realize commercial fusion plants in the first quarter of the next century.

Acknowledgement: *The author wishes to thank Dr. P. K. Iyyengar and Dr. P. R. Oastidar for their encouragement throughout this work. The author greatly benefited from discussion with scientists in the Plasma Physics Division, Bhabha Atomic Research Center. Particular thanks are due to Dr. A. S. Paithankar and Dr. T. Vijayan, who assisted in the preparation of this report.*