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OF
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MECHANICAL-ENGINEERING ASPECTS
OF
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ABSTRACT

The mirror approach to magnetic fusion has evolved from the original simple mirror cell to today's mainline effort: the tandem-mirror machine with thermal barriers. Physics and engineering research is being conducted throughout the world, with major efforts in Japan, the USSR, and the U.S. At least one facility under construction (MFTF-B) will approach equivalent energy breakeven in physics performance. Significant mechanical engineering development is needed, however, before a demonstration reactor can be constructed. The principal areas crucial to mirror reactor development include large high-field superconducting magnets, high-speed continuous vacuum-pumping systems, long-pulse high-power neutral-beam and rf-plasma heating systems, and efficient high-voltage high-power direct converters. Other areas common to all fusion systems include tritium handling technology, first-wall materials development, and fusion blanket design.

INTRODUCTION

Energy release by the fusion of atomic nuclei was first achieved in the laboratory more than 50 years ago. It wasn't until the early 1950's, however, that a significant scientific and engineering effort began on controlling thermonuclear reactions for the purpose of producing power. Since that time, two basic approaches have developed: inertial confinement and magnetic confinement. In inertial confinement, high-energy lasers or particle beams focused on a small fuel pellet cause the fuel to be compressed and heated rapidly (in microseconds) to fusion temperatures. In magnetic confinement, strong magnetic fields are used to contain a plasma fuel over relatively long periods (seconds) while it is heated to the necessary temperatures. This paper discusses the mechanical engineering aspects of one of the leading concepts in magnetic fusion called mirror confinement.(1)

Magnetic Fusion Energy Concepts

Nuclear fusion occurs when light atomic nuclei are brought together with enough force to overcome their coulomb repulsive forces. Four possible fusion fuels and their reactive products are shown in Table 1. The deuterium-tritium (D-T) reaction is currently of great importance because it is the easiest to initiate (requiring temperatures of 100×10^6 K or 10 keV[1]) and produces a great deal of energy. Ultimately, however, reactors may utilize the deuterium-deuterium (D-D) reaction because of the abundance of deuterium (a naturally occurring component of water), and the fact that the biological hazards of tritium are minimized. All of the reactions produce energetic particles which must be thermalized in a surrounding "blanket" material before usable energy is achieved.

In order to produce net energy ("breakeven"), the reactants must be confined long enough for the average fusion energy released to exceed the input particle kinetic energy required to initiate the reaction. This requirement is described approximately by the Lawson criteria which states that the product of particle density n (particles/cm^3) and confinement time τ (sec) must exceed a certain value for any given fuel and temperature, e.g., for the D-T reaction

TABLE 1 - NUCLEAR REACTIONS CONSIDERED FOR FUSION REACTORS.

Reaction	Energy released
$D + D \longrightarrow {}^3He_2$ (0.8 MeV) + n (2.4 MeV)	3.2 MeV
$D + D \longrightarrow T$ (1.0 MeV) + p (3.0 MeV)	4.0 MeV
$D + T \longrightarrow {}^4He_2$ (3.5 MeV) + n (14.1 MeV)	17.6 MeV
$D + {}^3He_2 \longrightarrow {}^4He_2$ (3.7 MeV) + p (14.6 MeV)	18.3 MeV

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[1] eV = 11,600 K

$$n\tau > 10^{14} \text{ sec/cm}^3$$

at a plasma temperature of 10 keV.

A conceptual design for a magnetic fusion reactor is illustrated in Fig. 1. At fusion temperatures, the plasma fuel is fully ionized, thus, magnetic fields can be used to confine the charged plasma particles. To avoid contamination and cooling of the plasma, the surrounding region must be held at a very high vacuum ($\sim 10^{-8}$ Torr). Auxiliary plasma heating devices may be needed to sustain the plasma temperatures. Assuming a D-T reaction, the lithium blanket serves to both thermalize the 14 MeV neutrons and to breed tritium according to the reaction

$$n + {}^6Li_3 \rightarrow T + {}^4He_2 + 4.78 \text{ MeV} .$$

The tritium produced in the blanket must be separated and reinjected with deuterium as the fusion fuel. Thus, a D-T reactor requires an initial inventory of tritium, but would be self-supporting in operation. A biological barrier surrounding the reactor is also required to satisfy environmental concerns associated with the tritium.

The energy delivered to the blanket must be carried away in the form of process heat (e.g., steam) through a heat exchanger just as in conventional thermal-electric power plants. In addition, energetic ions escaping the plasma can be converted directly to electricity and used to power auxiliary reactor equipment.

Magnetic Mirror Confinement

Magnetic confinement systems are generally classified as either "open" or "closed," depending on whether or not the magnetic lines close on themselves within the plasma confining volume (see Fig. 2). Tokamaks, the most prominent type of closed system, are a toroidal system in which an induced plasma current is used to create a stable confining magnetic field. Simple mirror machines, on the other hand, are a type of open system in which the magnetic field lines form a linear magnetic bottle before extending outside the confining volume. The magnetic field increases at each end of the system such that the axial velocity component of a plasma particle tends to decrease to zero and the particle is "reflected" back along the field lines. Some particles, however, have sufficient axial velocity components to escape the system through the end, known as the mirror systems "loss cone."

The first mirror machines, dating to the early 1950's, were of the simple mirror type shown in Fig. 2. These systems proved unsatisfactory due to gross magnetohydrodynamic (MHD) instabilities that resulted in rapid loss of the trapped plasma. This was improved by the invention of the Minimum-B mirror in which the magnetic field increases in all directions radially outward from the center or "magnetic well." The Minimum-B magnetic field was first created by the use of Ioffe bars in conjunction with circular coils (Fig. 3). Other topologically equivalent configurations include the yin-yang and baseball coils employed in recent experiments. These magnet configurations result, characteristically, in a twisted-bowtie plasma shape with the highest plasma density in the center of the magnetic well. In the mid-1970's, it was discovered that massive injection of energetic neutral fuel atoms into the plasma, called neutral-beam heating, served to elevate the plasma temperature and dramatically improve the performance of the machine. Unfortunately, reactor studies showed that a single cell machine was unattractive for reactor applications due to inherently low Q's (ratio of fusion power out to power input). Thus, alternate forms of mirror confinement were sought.

The next major advance in mirror systems was the invention of the tandem mirror.[2,3] In experiments with single-cell mirror machines, it had been found that the plasma electrons are more likely to escape than the ions, resulting in a plasma with a strong positive potential. By placing a minimum-B cell at each end of a solenoidal region, the strong electrostatic potential of the end "plugs" serves to

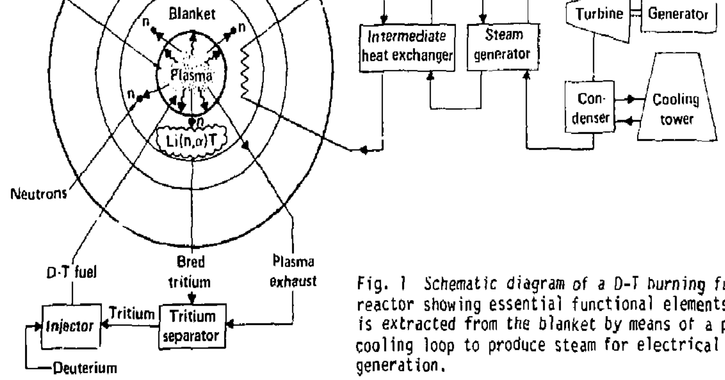
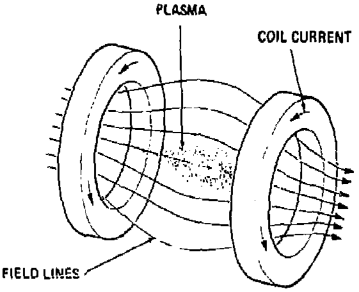
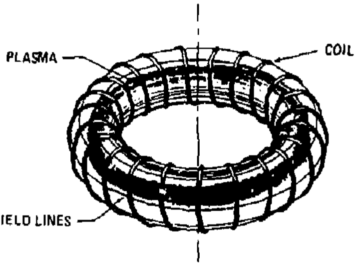


Fig. 1 Schematic diagram of a D-T burning fusion reactor showing essential functional elements. Heat is extracted from the blanket by means of a primary cooling loop to produce steam for electrical power generation.



OPEN SYSTEM - SIMPLE MAGNETIC MIRROR



CLOSED SYSTEM - SIMPLE TORUS

Fig. 2 Representations of open and closed magnetic confinement systems showing relationship between magnetic field lines and plasma confining volume.

Fig. 3 The "magnetic well" can be created by surrounding a mirror-type magnetic field by four current-carrying rods, referred to as Ioffe bars.

confine the positive ions in the central cell. Experimentally, this concept was proven on the Tandem Mirror Experiment (TMX) at Lawrence Livermore National Laboratory (LLNL) in 1979.

Current Mirror Fusion Experiments

Mirror fusion is being pursued at research centers throughout the world. Most current experiments use variations of the tandem mirror confinement concept.

One of the largest mirror experiments currently in operation is the TMX-Upgrade at LLNL (Fig. 4). This machine(4) is a modification of the TMX experiment to

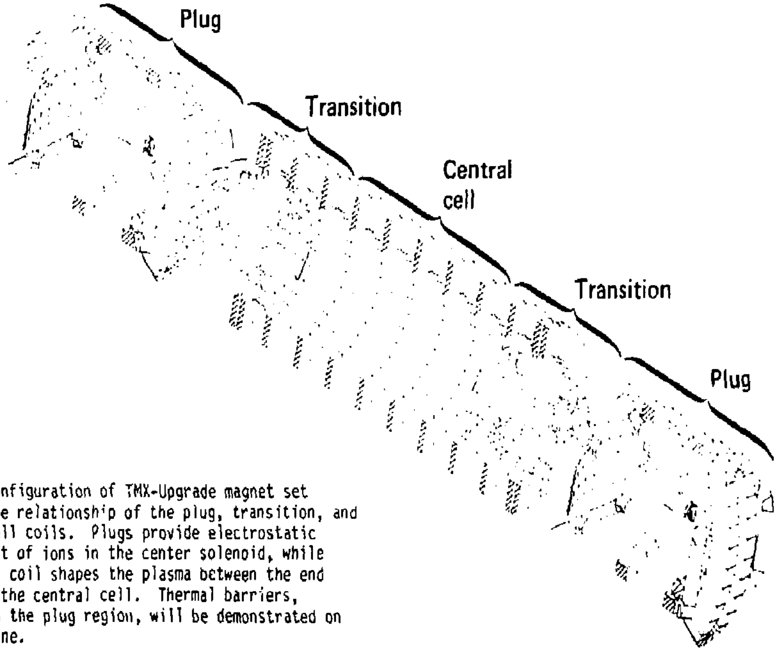


Fig. 4 Configuration of TMX-Upgrade magnet set showing the relationship of the plug, transition, and central-cell coils. Plugs provide electrostatic confinement of ions in the center solenoid, while transition coil shapes the plasma between the end plugs and the central cell. Thermal barriers, located in the plug region, will be demonstrated on this machine.

incorporate another innovation called the thermal barrier. The "barrier" consists of a region of reduced magnetic field strength, plasma density, and plasma potential between the end plugs and central cell. By application of high-energy rf heating and neutral-beam injectors for pumping of trapped ions, it is believed possible to maintain higher electron temperatures in the end cells, leading to improved electrostatic confinement in the central cell. The equivalent D-T performance of the TMX-Upgrade is expected to be on the order of 3 x 10^{11} s/cm^3. Reactor designs based on the thermal barrier show improved performance and less demanding magnet and plasma heating requirements for the end plugs.

At the University of Tsukuba, Japan, the GAMMA 10 experiment is nearing completion (Fig. 5). Slightly longer than the TMX-Upgrade, GAMMA 10 contains an axisymmetric mirror coil set at each end outside the mirror coils. These will be used for MHD studies and thermal barrier development. The GAMMA 10 experiment is very flexible, and will allow various modes of tandem mirror operations and plasma heating to be explored. Equivalent D-T performance on the order of $n\tau$ = 10^{12} s/cm^3 is expected.

The Mirror Fusion Test Facility (MFTF-B) under construction at LLNL is a large scale thermal-barrier tandem-mirror experiment employing superconducting magnet coils.(5) The MFTF-B magnet configuration (Fig. 6) contains high-field axicell plug coils (up to 12 Tesla) located at each end of the central solenoid region. A large transition coil serves to circularize the plasma emerging from the yin-yang anchor coils. The magnet coils are wound with NbTi conductor except for the high field Nb_3Sn plug coil, and are designed to be operated in 4.5 K pool-boiling helium. Long (30 s) and short pulse neutral-beam injectors and high power radio-frequency (rf) provide the necessary plasma heating. The MFTF-B experiment is expected to achieve equivalent D-T performance near breakeven (Q = 1) when completed in 1985. Recent engineering tests (February 1982) demonstrated the performance of the first two yin-yang superconducting magnet coils, as well as cryogenic, vacuum, and control subsystems.

There are a number of other experiments contributing to mirror confinement research. These include the Symmetric Tandem Mirror (STM) at TRW which employs various forms of rf heating, and the proposed axisymmetric TARA experiment at MIT which would utilize minimum-B end plugs for MHD stability. The Soviets have also reported experimental results related to thermal barrier performance.

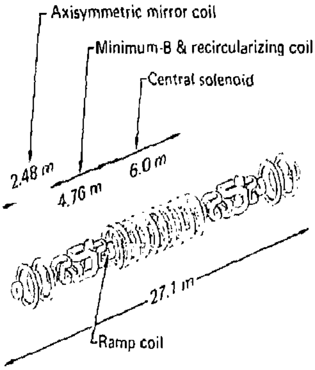


Fig. 5 Coil geometry of GAMMA 10. The GAMMA 10 experiment is a very flexible research system capable of three modes of tandem-mirror operation (quadrupole, axisymmetric, and hot-electron-ring stabilized); three plasma heating systems are used.

ROAD TO COMMERCIAL POWER

Following the operation of MFTF-B, the mirror program plans several steps in going from plasma confinement experiments to power producing D-T reactors.(6) The two most significant differences between physics experiments and reactor-like devices are the introduction of tritium with its inherent safety considerations and the production of the large quantities of 14 MeV neutrons that induce radiation in the machine structures and require shielding.

The first major step toward a prototype reactor will be the construction of a Technology Development

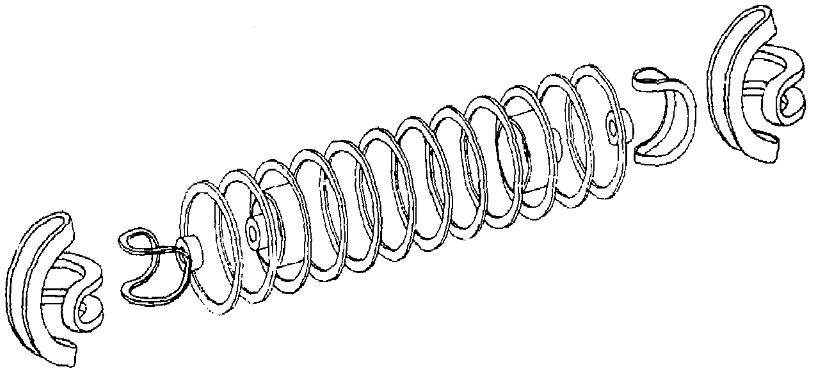


Fig. 6 Configuration of the MFTF-B magnet set. All 22 superconducting coils are wound with a Nb-Ti conductor except for a Nb_3Sn insert in the small high-field plug coils located at each end of the solenoid. The MFTF-B will explore scaling of the thermal-barrier tandem-mirror physics while demonstrating relevant engineering technologies.

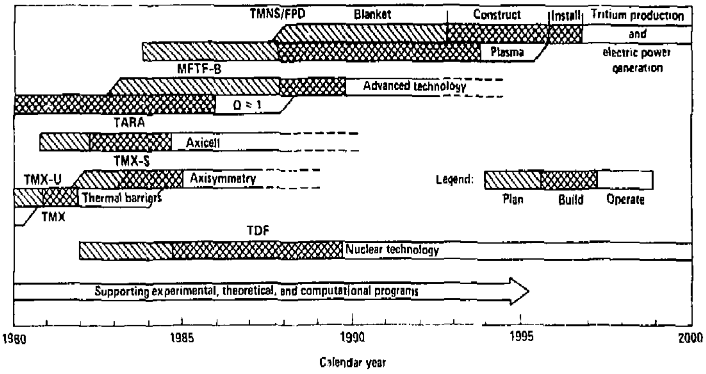


Fig. 7 Tandem mirror main sequence.

Facility (TDF). TDF will be a small, driven (negative power balance) device producing a large flux of fusion neutrons and having all the engineering subsystems of a power reactor. This would be followed by Tandem Mirror Next Step (TMNS), an electrical breakeven fusion reactor demonstrating the final size scaling to power reactor plasmas. The final device to be built before a commercial reactor would be a Tandem Mirror Demonstration Reactor (TMDR). The TMDR is required to operate as a reliable reactor that is not necessarily economically competitive with other electrical generation systems, but it should demonstrate the technology of commercial reactors. The timing of these projects through TMNS, as presently envisioned, is shown in Fig. 7.

The basic technology for these devices is a natural evolution from that of MFTF-B as well as other advanced confinement experiments. The real challenge will be to develop the experimental short pulsed hardware into reliable, maintainable steady state systems.

Radiation shielding requirements will drive the physical size of many of the reactor components, and considerations for radiation and tritium safety will have large impacts on the requirements of the conventional facilities and direct reactor support systems.

TECHNOLOGY DEVELOPMENT AREAS

The physics of mirror systems has made dramatic progress in recent years. As physics theory is born out over the next few years by experiments currently in progress and attention focuses on reactor technology, engineering must play a more prominent role. This section addresses those areas where significant challenges lie ahead for mechanical engineers.

Large High Field Magnets

As the success of the magnetic fusion program has grown, so has the physical size of the experiments. Facilities such as MFTF-B employ magnet systems approaching the size of those proposed for commercial reactors. Higher magnetic fields (> 20 T) are proposed for some mirror reactors. To avoid the tremendous energy dissipation of large copper coils, all commercial reactor studies project the need for large, high field superconducting magnet coils.

Advancements are necessary on several fronts to build these systems. Niobium-titanium is currently the preferred superconductor for applications in magnetic fields less than 8 T. At higher fields, Nb_3Sn is required, but reliable production techniques for the conductor are still under development. The brittle properties of the conductor itself make it difficult to wind all but the simplest coils.

The major cost factor in superconducting magnets is the structural materials and their fabrication. Electromagnetic loads increase as the square of the magnetic field. Thus, large, high-field magnets, operated at cryogenic temperatures, represent a critical design application. The development and qualification of high strength fracture-safe structural materials for cryogenic magnet service is an important area of research.

Superfluid helium II is being investigated for use in superconducting magnets. Its superior heat transfer characteristics could potentially result in more compact magnet coils, thus saving money in structural components. Experimental programs to verify the performance of helium II and the development of reliable, efficient helium II cryogenic plants may be required.

High-Speed, High-Capacity Continuous Vacuum-Pumping Systems

Vacuum engineering is one of the base technologies of magnetic fusion. To avoid contamination or cooling of the plasma, the background pressure around the fusion plasma must be maintained at approximately 10^{-6} Torr. This is made difficult by the fact that mirror machines must be continuously refueled by the injection of energetic particles into the plasma to replace those consumed or lost from the ends. To achieve the necessary high pump speeds, some form of surface pumping must be employed. The two methods available are active metal pumping (gettering) and cryopumping (LHe cooled surfaces). Both are batch processes requiring periodic degassing into a collection system that has an impact on the tritium inventory (safety) of the reactor. Although the basics are well known, a significant development program is required to develop specific designs that can be optimized for pumping performance and reliability.

Plasma Heating and Fueling

Tandem mirror machines, like all magnetic fusion devices, require a population of hot ions. These may be supplied and heated in various ways. In the case of mirror fusion experiments, the energetic ions are supplied by neutral particle injection, a process that both fuels and provides the required heating. Radio frequency energy is also added to the tandem-mirror end region as a means of improving confinement.

Neutral-beam injection systems for reactors must operate in a steady-state mode and have high reliability. The technical issues to be addressed in going from today's pulsed systems to reactor systems are active cooling, radiation damage, and maintainability. By their nature, the neutral beamline components must face a flux of 14-MeV neutrons produced in the reactor plasma. Radiation damage to insulators, erosion of electrodes, and ion source degradation must be reduced to the extent that these units can operate for several thousand hours without failure.

When reactor conditions are reached in future machines, the central-cell plasma will be "ignited"; that is, all the required heating of the power producing plasma will come from the α particles produced by fusion reactions. Fuel must still be added, probably in the form of pellets of frozen deuterium and tritium injected at high velocities to penetrate the reacting plasma. Pellet injectors capable of generating small pellets of frozen D_2 and T_2 and accelerating them to velocities several thousand meters/sec at high repetition rates (hundreds/second) must be developed.

RF for mirror machines is employed as Electron Cyclotron Resonance Heating (ECRH) and perhaps as Ion Cyclotron Resonance Heating (ICRH). Presently, ECRH is provided by pulsed 28-GHz and 60-GHz gyrotron tubes. Continuous-operation tubes are under development, and the principal additional tasks will be to improve efficiency and unit power for application to reactors. ICRH tubes and power supplies are of existing technology. The challenge is in developing antennas that can operate satisfactorily in the magnetic, radiation, and plasma environment.

Direct Energy Conversion

Mirror fusion systems inherently eject energetic ions from the plasma through the loss cone. These ions can be collected on positively-biased electrodes and their kinetic energy converted to electrical energy with about 50% efficiency (see Fig. 8). The resulting electrical power can then be used to power system auxiliaries such as neutral-beam injectors, thus improving the overall plant efficiency. Direct conversion systems can also be used to recover the energy from neutral-beam injectors that has not been absorbed by the plasma.

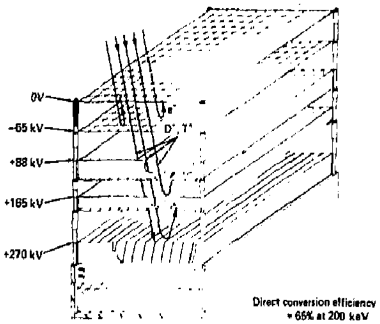


Fig. 8 An example of a "venetian-blind" type direct-energy converter. High energy impinging particles are decelerated and captured by the grids at efficiencies approaching 65% at 200-keV particle energies.

Further development work is required in the area of high-voltage, high-power designs. These inherently involve significant heat transfer, gas handling, and material considerations. Rugged, reliable, and efficient high power-density direct converters are the ultimate goal of this work.

High Heat Flux Components

Many components of fusion reactors are subject to high heat fluxes, up to several MW/m^2. In mirror systems, this includes neutral beam, ion and plasma dumps, first walls, rf antennas, and magnet heat shields. Closely coupled to materials development work, the development of steady-state heat-transfer components is a crucial element in reactor engineering.

Up until now, experiments have been relatively short pulsed and low power so that passive dumps relying on the thermal inertia of the dump have been sufficient to control peak temperatures. As continuous reactor operation is approached, such factors as thermal stress, boiling heat transfer, thermal fatigue, and high temperature material characteristics will become crucial. A systematic investigation to establish the thermo fluid, thermomechanical design data base is needed to prepare for fusion reactor engineering.

Tritium Handling

Tritium handling considerations are common to all fusion reactor systems. The radiation hazard, particularly that of tritiated water, makes handling and clean-up system design the most severe safety design problem in a fusion reactor system. Other than the differences in fuel quantities and mix, the tritium systems for all fusion systems will be very similar.

Fusion Materials

High radiation loads, temperature extremes, high magnetic fields, and the presence of tritium all combine to make the material problems of fusion reactors particularly difficult. The relatively long time necessary to qualify a new material for reactor service (approximately 25 years) forces the program to either start early, as with present work on ferritic steels, or rely on existing materials, such as the austenitic stainless steels previously qualified for fission reactors.

Reactor Maintenance

Fusion reactors, by their nature, are large complex devices that have many highly stressed and sensitive components exposed to neutrons and gamma rays. The external cost of fuel is negligible and, therefore, the cost of electricity is largely determined by the original capital cost plus operating manpower costs. The economics of fusion electricity will then be highly dependent on the system availability.

Maintenance of all internal structures must be done with remote tooling because of the large gamma-ray flux that will be present throughout the life of the device. It is obvious that the engineered systems must be designed for long reliable life, and that the whole facility be carefully laid out to maximize the efficiency of maintenance operations and to minimize remote operations. It should be noted that remote operations typically take 5 to 20 times as long than an identical task done in the contact mode.

Reactor Products

The products of the fusion reactor are energetic particles, most typically 14-MeV neutrons and 3.5-MeV α particles. These are not in themselves very useful, so their energy must be converted into some practical product.

Three possible products are seen for tandem mirror reactors: electricity, fissile fuel, and hydrogen. Electrical power generation is the primary goal of the program in the U.S. because it gives the direct promise of replacing both fossil fuel and fissile fueled base loaded power plants. The production of fissile fuel from depleted uranium or thorium would be a way to extend our supplies of fuel for light water reactors, and the conditions required to do this economically are somewhat easier to achieve than for direct electrical power generation. The production of hydrogen by high temperature chemical reactions has the promise of providing transportable environmentally clean fuels in the future.

All three of these processes require the engineering of "blanket" and heat removal systems that produce the desired product, plus sufficient tritium to fuel the reactor. Each approach presents its own problems in thermal hydraulics, corrosion, radiation damage, tritium separation, and maintenance.

CONCLUSION

The mirror fusion program has made several orders of magnitude improvement in demonstrated performance in the past five years. We are rapidly approaching the point where engineering technology, rather than plasma physics, will become the critical path to commercial fusion power. Mechanical engineers will play key roles in the areas of magnetics, vacuum, plasma heating/fueling, and reactor product handling systems.

ACKNOWLEDGMENTS

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