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Challenges of Nuclear Fusion

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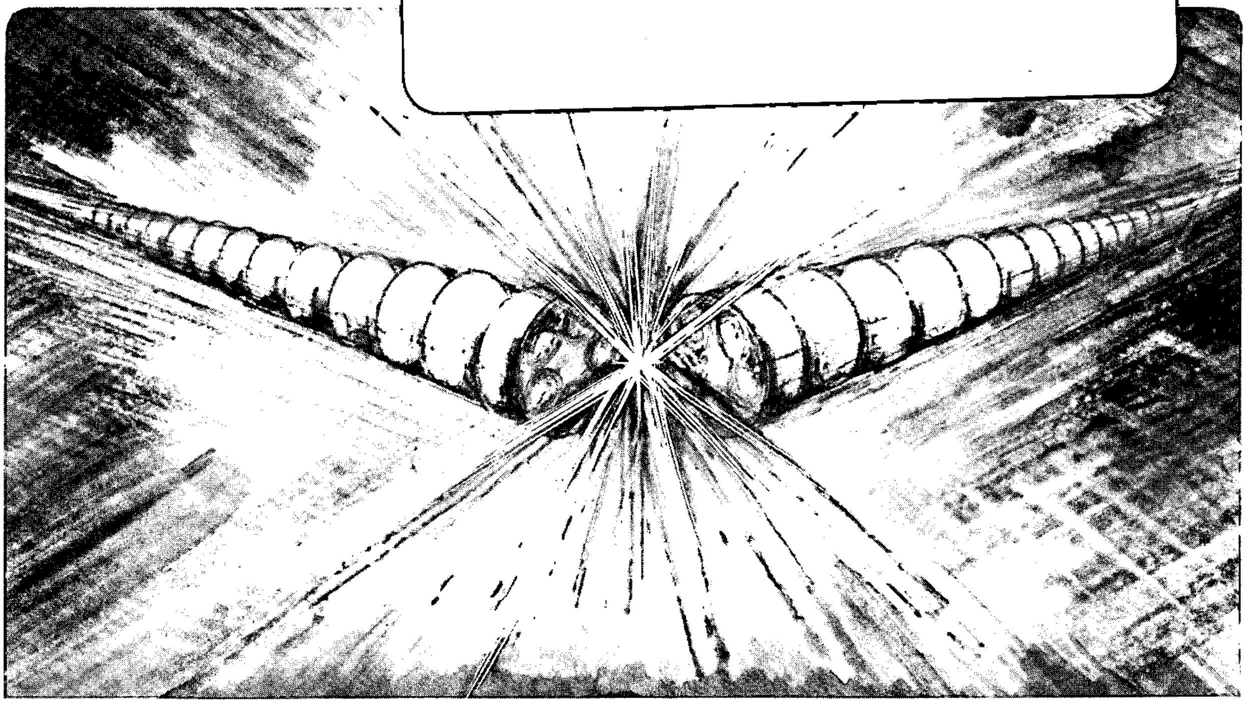

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CHALLENGES OF NUCLEAR FUSION*

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Abstract - After 30 years of research and development in many countries, the magnetic confinement fusion experiments finally seem to be getting close to the original first goal: the point of "scientific break-even." Plans are being made for a generation of experiments and tests with actual controlled thermonuclear fusion conditions. Therefore engineers and material scientists are hard at work to develop the required technology. In this paper the principal elements of a generic fusion reactor are described briefly to introduce the reader to the nature of the problems at hand. The main portion of the presentation summarises the recent advances made in this field and discusses the major issues that still need to be addressed in regard to materials and technology for fusion power. Specific examples are the problems of the first wall and other components that come into direct contact with the plasma, where both lifetime and plasma contamination are matters of concern. Equally challenging are the demands on structural materials and on the magnetic-field coils, particularly in connection with the neutron-radiation environment of fusion reactors. Finally, the role of ceramics must be considered, both for insulators and for fuel breeding purposes. It is evident that we still have a formidable task before us, but at this point none of the problems seem to be insoluble.

Introduction

It has been almost 30 years since the quest for nuclear fusion power has been declared an international endeavor, at the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, at Geneva in 1958.(1) Considerable advances have been made since that time, of course, and progress has been steady, although sometimes aggravatingly slow. Many of the problems turned out to be much more difficult than first anticipated, particularly in connection with plasma instabilities and modes of behavior that interfered with the effective energy confinement at high temperatures.

At present we can say with confidence, however, that we are close to the primary major physics goal for fusion: the achievement of controlled thermonuclear ignition conditions in confined hot deuterium-tritium plasmas. As a matter of fact, all three so-called "Large Torus" magnetic-confinement experiments in operation at present: the European Community's Joint Undertaking JET at Culham, U.K., the Japanese Atomic Energy Research Institute's JT-60 at Naka-Machi, Japan, and the US Department of Energy's TFTR at Princeton, USA are expected to reach the conditions for effective "scientific break-even", where the thermonuclear power that could be generated in D-T reactions would equal the heating power (see Fig. 1). Both the European and the American experiments are scheduled to end up with a number of runs involving tritium, so that the consequences of copious D-T reactions will become noticeable. The physicists are primarily interested in the effects of the generated 3.5 MeV α-particles on the plasma, while the engineers and chemists will be able to see the effects of the 14 MeV neutrons on all the structural materials surrounding the plasma.

In this paper the present status of fusion research is summarized and critical issues of technological development are enumerated, with the emphasis on toroidal magnetic confinement systems.

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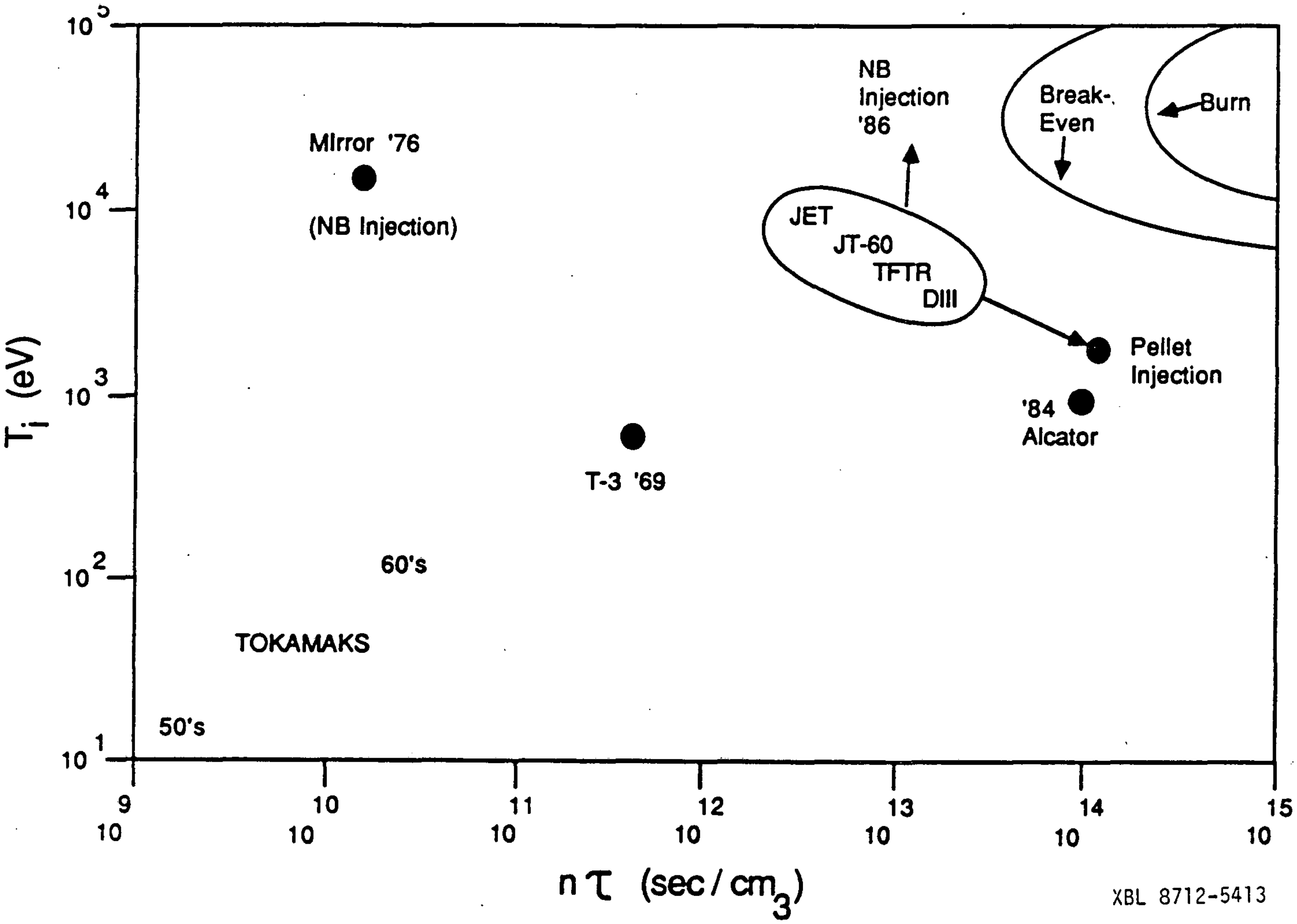


PROGRESS IN TOROIDAL CONFINEMENT. The Central ion temperature, T_i expressed in eV, is plotted against the Lawson figure-of-merit (ion density x energy confinement time) $n\tau$ in seconds per cubic centimeter for various tokamaks.

Figure 1

Recent Progress in the Physics of Toroidal Magnetic Confinement

Two recent developments have significantly improved the outlook for future toroidal magnetic confinement fusion reactors. First, the fueling by means of solid pellet injection has been demonstrated to work better than anticipated. It appears that it will not be necessary for the pellets to penetrate all the way to the plasma minor axis. Rapid mixing in the core seems to be adequate for the purpose without detrimental effects on the confinement as long the pellets penetrate deeply, to the proximity of the axis. Lawson figures-of-merit $n\tau$ in excess of the critical value of 10^{14} sec/cm^3 for power break-even have been reached in this manner, albeit at insufficient temperatures for the fusion reactions(2)(3) (see Fig. 1). This technique is particularly promising in connection with the second important recent development, i.e., the progress toward steady state operation of current-carrying toroidal systems.

The stellarator concept of toroidal magnetic confinement has always been thought of as a steady-state configuration. However, the required twisted coil-structure has been an impediment. In contrast, axisymmetric configurations, such as the tokamak, while simpler in structure, have had the disadvantage of requiring induced and therefore necessarily pulsed currents for their operation. In recent years noninductively driven ring currents have been demonstrated in a variety of ways, via the non-symmetric launching of diverse types of waves in the plasma as well as via the injection of high-power neutral beams. This opens the possibility of steady state driven toroidal currents,(4) and several proposals for the next generation of toroidal confinement experiments have incorporated such current-drive options. A particularly intriguing feature of high-temperature plasma

in this situation is the predicted so-called "bootstrap" effect in which the radially outward diffusion of plasma across the magnetic field generates an additional current so that only a fraction of the total current needs to be driven externally.(5) This bootstrap effect has recently been demonstrated convincingly, particularly for certain types of neutral-beam injection tests on the TFTR experiment at Princeton.
The combination of pellet fueling and bootstrap-enhanced steady state driven currents, possibly even accompanied by improved confinement characteristics,(6) has given a considerable boost to the magnetic confinement prospects for ultimate success. It has therefore become important to give increased attention to the problems of materials and technology for fusion reactors. Indeed, the success of fusion energy depends as much on progress in technology and material science as it does on advances in plasma physics.(7)

Principal Elements of Fusion Technology and Materials Development

The engineering principles common to all magnetic-confinement fusion reactors are most conveniently summarized by means of a simplified schematic sketch(8) shown in Fig. 2. An engineering drawing of a conceptual design for a possible Fusion Experimental Reactor, the International Tokamak Reactor (INTOR)(9) as a particular example is reproduced in Fig. 3. The principal elements requiring development are easily recognized. We list them here in the order of increasing distance from the hot plasma:

1. The "limiter" is a solid ring or belt made of, or coated with, low-Z material, such as graphite on beryllium. It is not shown in Figs. 2 and 3 because it is hoped that actual reactors will operate with magnetic, non-material limiters. When it is present, however, as in most of today's experiments, it is the component subjected to the most severe conditions since it is closest to the hot plasma. It literally touches the plasma, thereby defining the plasma edge. In its shadow sensitive components such as RF antennas and diagnostic equipment tend to be protected from plasma bombardment. During occasional so-called "disruptions" large fractions of the entire plasma energy content may be deposited on parts of the limiter (or armor) in a short fraction of a second. Limiters should be sturdy enough to survive such disruptions.

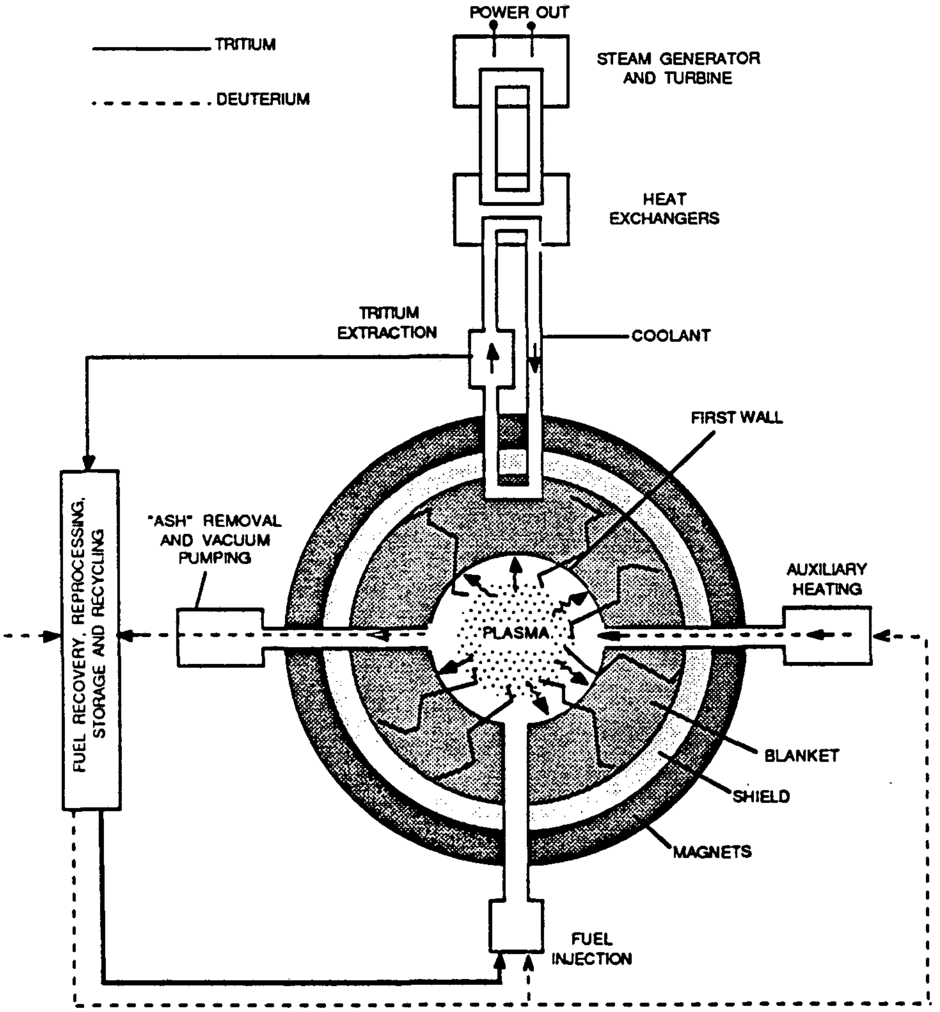
2. The first wall is a liner of specially developed material that surrounds the entire plasma. It is generally not the vacuum envelope but a replaceable insert since it is expected to deteriorate through bombardment by plasma particles, intense thermal radiation, and the neutron flux from the fusion reactions. Research on plasma-material-interaction (PMI) and on high-heat-flux (HHF) components address primarily the issues concerned with the first wall (and with solid limiters, if these are needed). Since material from these surfaces is bound to be sputtered off or evaporated and enters the plasma as contamination, low-Z elements are usually preferable in their composition, but the response to neutron bombardment is of course also an important consideration.

3. Divertor plates must be used as the principal surface areas for contact between plasma and the solid surroundings in conjunction with magnetic diverters, shown in Fig. 3. In this scheme most ions and electrons at the outer edge of the plasma are prevented from reaching the first wall or a solid limiter by being diverted in a so-called scrape-off layer along the magnetic field lines towards a "burial chamber" in which they impinge on and recombine at the divertor plates. Much of the resulting neutral gas is then pumped off and only a small fraction returns directly to the hot plasma. Search for the most suitable materials and optimization of the design is a continuing task.

4. The blanket is the crucial component where the fusion neutrons give up their energy (nearly 80% of the total fusion energy released). It is also the region where these same neutrons can be used to "breed" the needed tritium fuel by transmutation of lithium. This is therefore the region where most of the nuclear engineering comes to play.

5. A radiation shield must surround the blanket to reduce drastically the neutron flux and most other radiation reaching the external parts of the reactor.

6. The magnetic field coils that are needed to produce the toroidal field (TF) and those that are used to create and adjust the poloidal field (PF) and thereby control the position and shape of the plasma are outside the shield. In most advanced designs they are superconducting and hence sensitive to radiation. The development and testing of suitable large superconducting coils has been a major effort in fusion technology.



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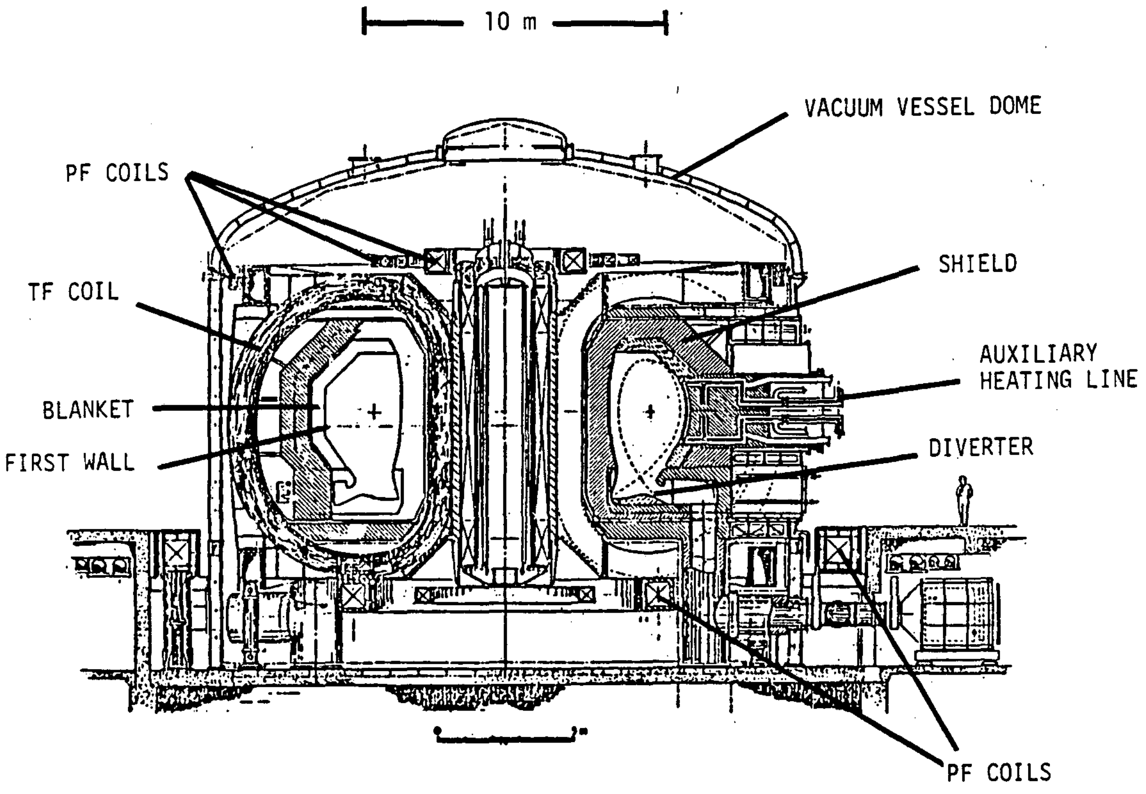
ENGINEERING PRINCIPLES common to all magnetic fusion reactors are diagrammed. A magnetic field must confine the fusion plasma; an auxiliary heating system must help to raise its temperature; a fuel-recycling system must keep it pure and well supplied with thermonuclear fuel. The heat the plasma releases must be withstood by the first wall of the reactor. The neutrons the plasma releases must penetrate into the blanket, where the energy the neutrons deposit must be transferred (in the form of heat) to a coolant. In turn the coolant can generate steam, the steam can drive turbines and the turbines can generate electricity. Nuclear reactions in the blanket must also "breed" tritium, which is radioactive and is extremely rare in nature.

Figure 2

From "The Engineering of Magnetic Fusion Reactors," by Robert W. Conn. Copyright (c) 1983 by Scientific American, Inc. All rights reserved.



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INTOR Design 1985, Elevation View

Figure 3

7. Auxiliary components, such as suitable coolants, heat exchangers, tritium extractors and fuel processing plants as well as fuel injectors, supplementary heating systems, and finally noninductive plasma-current-drive techniques all still require technological developments. A substantial part of this development has to address materials problems, particularly in connection with the reactor radiation environment.

Issues and Recent Advances in Materials Research and Development for Fusion

Much progress has been made over the last decade in the development and selection of materials with the requisite properties for fusion reactors. The status has recently been summarized in a document published by the U.S. Department of Energy(10) and relevant excerpts are quoted here.

1. Increased Service Life for Structural Materials - A key component in a fusion power reactor is the blanket structure in which the energy released in the fusion reactor is converted to usable heat. This conversion occurs when high energy neutrons from the fusion reactor strike the blanket. This heat is, in turn, extracted by a coolant to be converted into useful work. The structural materials that absorb the neutrons are subject to two effects: changes in mechanical properties and changes in dimensions, most often in the form of swelling. Both changes are caused by damage to the material's crystal structure by energetic neutrons. The swelling is aggravated by the agglomeration of helium (and perhaps hydrogen) produced in nuclear transmutation reactions.

When neutron damage becomes too severe, the blanket structure - especially the so-called first wall that faces the plasma directly - must be replaced. The challenge when the materials research effort began in the mid-1970's was to increase predicted first wall lifetimes by at least tenfold from an unacceptable 0.4 years to 4 years or more. Predictions now are for service lives at least five times those that could be assumed in the mid-1970's, and further increases are projected. As a result, the feasibility of reactor-grade materials has been established.

Improvements in structual materials are expected because of advances over the past 10 years in understanding the fundamental processes of radiation damage and extrapolation from the growing data base on the subject. For example, it was originally predicted that the fatigue resistance of structural materials would be seriously degraded in a fusion reactor; this has been dispelled by experimentation. Substantial improvements have been made in reducing the swelling of austenitic steel, one of the primary candidate alloys for reactor structural materials. These improvements result from better alloy mixes and advanced manufacturing and processing techniques.

The question is no longer whether structural materials exist from which a commercial fusion reactor can be built; they do. For both the experimental and engineering community, the question now is how to modify known materials in ways to decrease cost, improve performance further, and minimize waste disposal requirements.

Of particular interest are structural materials that minimize residual induced radioactivity so that they can be disposed of safely without the long-term hazard associated with fission waste. Here, too, much progress has been made toward practical choices of first wall and structural materials that can be disposed of by shallow burial, perhaps at the plant site. Research on such low waste alloys will continue to be an important component of fusion materials research.

An excellent review of these issues and a discussion of the required research and development, experimental tests and needed facilities has recently been put together by Abdou et al.(11)

2. Durable Magnet Materials - At the beginning of the fusion program, information was needed about the maximum tolerable neutron exposure for superconducting magnet components: the superconductor, the stabilizer, and the insulator. Without this information, early reactor designs had to assume poor radiation tolerance and accommodate massive and costly shielding to protect the magnets. Based on current tests, the fusion materials program has now confirmed that the superconducting materials with the best operating characteristics for fusion magnets (Niobium-Titanium and Niobium-Tin) are sufficiently durable for magnets to function as intended with much less shielding than was thought possible earlier in the program.(12) This will lead to savings of millions of dollars in construction costs for a power reactor.

3. High Performance First Wall Materials - Even though the plasma fuel is confined in a "magnetic bottle" during normal operation, it still drifts outward until it touches and is neutralized on "limiters," or deflected magnetically towards diverter plates, protecting the vacuum chamber walls. There the particles dislodge atoms or other particles, which enter the plasma as impurities. Once in the plasma, the impurities act like wet wood thrown on a fire. They absorb and radiate energy intended to heat the plasma without contributing to the energy producing process. To make matters worse, impurity atoms (which do not react) dilute the fuel plasma. The heavier the impurity atom, the worse the energy drain.

By 1978 energy losses due to impurities became the critical impediment to raising plasma to the temperatures required for energy breakeven. A solution came from the understanding of the plasma-edge environment that had been accumulating in plasma physics studies, and from the knowledge gathered in materials research about the interaction between the plasma particles and materials. Knowledge of the mechanical and thermal stresses on the limiters led to a search for superior materials to limit the plasma. The answer was to fabricate the limiters out of carbon in place of the heavier refractory materials which were in use at the time.

The change in material for limiters was responsible for a 30 million degree Celsius increase in plasma temperature on the PLT, for example.

A summary of the topic of high-heat-flux (HHF) components has been given, for example, by Gauster et al.(13) A recent explicit report on experimental work with various coatings on first walls, armors and limiters in fusion experiments has been published by Smith and Whitley.(14) The research and development on Plasma-Materials Interactions (PMI) and HHF components in the U.S. Fusion Program has been described most recently by R. W. Conn,(15) in connection with an international Technical Working Party (TWP) (Japan, the European Community, and the U.S.A.).

4. Ceramics for Insulation and Fuel Breeding - Ceramics are required for a variety of insulator applications in a fusion reactor, some of which will receive high neutron exposure. In addition, ceramics containing lithium are promising candidates for tritium breeding materials.(16)

When the fusion materials program began, the little information available on radiation effects in ceramic insulators suggested that poor performance could be expected. This meant that reactor designs would have to accommodate the need for frequent replacement of key components. The fusion ceramics testing program has since demonstrated that a number of ceramics offer extended lifetimes in fusion reactor applications. Furthermore, increased understanding of degradation mechanisms has led to effective methods of enhancing radiation resistance.

The importance of ceramics takes on added dimensions in light of promising indications of their usefulness in breeding tritium in the blanket. If the blanket contains lithium, some of the neutrons striking it will interact with the lithium to produce tritium, a constituent of reactor fuel that is not found in nature. Since lithium is difficult to handle in pure forms, a solid lithium compound such as a ceramic containing lithium could offer considerable advantages. Previous doubts that tritium could be successfully extracted from a solid compound have been dispelled following an experiment in which tritium was produced from a lithium ceramic compound while it was being bombarded with neutrons from a fission reactor. It has also been shown that ceramic compounds will hold up adequately under the neutron bombardment of the fission environment.

Conclusion

1. Tokamak Reactor Concepts - For the first time in the history of fusion research, there seems now to be a substantial and reliable experimental basis for the detailed description of the fundamental scientific and technology requirements of a magnetic fusion reactor. The key issues have gradually been revealed by the detailed series of conceptual reactors designed and produced over the last 15 years. The object of these studies is to describe a plausible fusion reactor based on the underlying physics and reasonable extrapolations of the technology.

Research and design studies on a broad front have made it possible to describe the forms that commercial fusion reactors might take. The required technologies, the plant power balance, the capital and operating costs, and the safety and environmental features of fusion power can all be estimated. A reactor study is performed by a multi-disciplinary team of physicists and engineers that must keep one eye on present-day experiments and theory and one eye to the possible future reactor end-product. The feedback from this study then steers it towards the safest and the most environmentally benign application of fusion energy.

Perhaps the most important example of these studies is the International Tokamak Reactor (INTOR) that has extended over the past eight years, involving teams of experts from Europe, Japan, the USSR and The USA. Excellent summaries of their reports have been published in Nuclear Fusion.(17) It is hoped that such efforts will continue with increased vigor, since it is generally recognized that the next version, the Fusion Experimental Reactor, will be so large and costly that worldwide collaboration will be essential.

2. Alternatives

This presentation has concentrated on tokamaks because they are preceived to be closest to the scientific "break even" goal. Not surprisingly also, tokamaks have enjoyed the largest effort, worldwide. This is not to say, however, that the tokamak concept is considered to be the best or the most promising by everyone. As mentioned before, stellarators are toroidal confinement systems which do not require a toroidal current and hence are considered potentially superior by some. Furthermore, both tokamaks and stellarators tend to lead to very large reactors, which is not exactly popular with the power industry. Consequently, there are a number of alternate approaches, such as compact toroids, pinches, moving rings, etc., that are smaller and operate at higher density and usually as transients. All these concepts have certain advantages and disadvantages when compared to the tokamak. The same is true for the non-toroidal systems, the so-called linear (or open) configurations, such as the mirror machines. Even the completely different scheme of generating fusion power by compressing and igniting fuel pellets, the so-called inertial confinement fusion (ICF) can be listed in this connection. All these approaches have certain specific and different technological problems. But a large number of the materials issues are the same, or at least similar, particularly in connection with the reactor radiation environment, the heat transfer and the fuel breeding aspects. In this sense therefore, the tokamak reactor can serve as a good example to describe the challenges of nuclear fusion power.

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