the next 3 to 5 years these uncertainties should be resolved.

A three-phase strategy for demonstrating fusion power generation at a committed site has been proposed in this article. It is emphasized that this is a strategy and not a detailed plan. Nevertheless, the strategy outlined here suggests that tokamak fusion power could be demonstrated with reasonable expenditures of money.

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Engineering Limitations of Fusion Power Plants

Problems related to radiation damage and plant costs may prevent the practical application of fusion.

W. E. Parkins

During the past few years, increasing attention has been directed to preliminary engineering studies of possible fusion reactor power plants. These studies have employed the best available theoretical extrapolations of results of confinement experiments in order to predict operational parameters for the power-producing plasma. While no net power-producing fusion plasma has yet been demonstrated, the engineering studies are important in providing guidance to the development program and in pointing out significant practical problems to be faced, once it is learned how to achieve useful thermonuclear reacting conditions. This article does not deal with the difficulty or probability of success of plasma confinement, but instead focuses on engineering aspects of proposed full-scale plants believed to be of critical importance to the future of fusion power.

One problem area that has been stressed is the difficulty of processing and containing the tritium in a fusion plant employing the deuterium-tritium (D-T) reaction. This subject was evaluated in a section of the first report of the Atomic Industrial Forum Committee on Fusion (*1*). The conclusion was that the technology is available to meet the operational requirements and that the principal concern is the impact that plant design features for tritium handling might have on total capital costs. Another problem area treated was related to the acceptability of plant operation from the environmental and safety standpoints. Again, it was concluded that fusion plants will be able to meet all environmental and safety requirements. The greatest difficulty appears to be that of adequately limiting the release of tritium during normal plant operation and as a result of postulated accidents. This then reflects back on the plant design features that will ensure adequate tritium containment, and the effect on capital costs again becomes a principal point of concern.

There are other features inherent in a fusion reactor plant that will force increases in the cost of the initial installation, and the magnitude of the total investment is recognized to be a problem of critical importance to the eventual successful application of fusion power (*1*). In this article some of the engineering factors bearing on capital costs will be evaluated. A second very serious engineering problem area discussed is that of the limited operating life of the reactor vessel, caused by the deleterious effects

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of the radiation to which it is subjected. Periodic replacement of this vessel will unfavorably affect plant availability and operating costs (*1*).

Most of the conceptual studies of full-scale fusion power plants have been based on the tokamak-type reactor. It is also used for the purpose of illustration here, but it should be noted that most of the engineering considerations treated apply to other fusion plasma confinement methods, whether magnetic or inertial. Reference is made here to the preliminary designs prepared by the University of Wisconsin Fusion Feasibility Study Group. Their series of tokamak reactor plants, designated UWMAK I, II, and III, represent the most thorough effort yet completed to evolve a workable fusion power plant design.

Summary. If conditions for a net power-producing thermonuclear reaction are ever demonstrated, difficult engineering problems must still be overcome. Two such obstacles to any practical application of fusion power are the magnitude of the plant capital cost and the limited lifetime of the reactor vessel. Among the factors contributing to the high initial cost is the constraint heat removal places on reactor size. This results from a fundamental engineering disadvantage of the fusion concept. The problem of limited reactor vessel operating life is inherent in the use of thermonuclear reactions, such as deuterium-tritium, which release damaging energetic neutrons.

Impact of Plant Capital Cost

It must first be recognized that the overriding figure of merit that will determine the acceptability of fusion power plants by utilities will be the competitiveness of the net cost of electrical energy produced. The history of the industry bears out that no other consideration can compensate for an appreciably higher cost of power. Then since the total cost of power produced by a fusion plant would be almost entirely contributed by charges against the capital investment, the future successful large-scale application of fusion in central station electrical generation will be critically dependent on these initial plant costs.

Concern that the magnitude of capital costs might rule out any practical application of fusion, even if and when its feasibility has been demonstrated and operating experience has permitted engineering optimization of plant designs, has been expressed by representatives of the electric utility industry. This and other problems facing the fusion development program have been discussed in a series of articles by Metz (*2*). The need to move in the direction of less expensive plant designs had already been recognized by many workers in the field, and a number of ideas exploring this possibility have been brought forth (*3*).

The portion of the fusion power plant having the greatest capital cost impact, and the portion representing the greatest design unknown, is the so-called nuclear island. It includes the reactor vessel, all internals, vacuum systems, neutron absorbing blanket, shields, all magnet and coil systems, neutral beam injectors or other auxiliary means of plasma heating, devices for fueling, means of impurity control and "ash removal," reactor instrumentation and control systems, and associated remote handling equipment. Whatever the design features of all of these components entail, it is apparent that the most effective approach to cost reduction would be through overall size reduction.

To illustrate, the UWMAK I, with an output of 1500 megawatts electric (MWe) (*4*), required the following amounts of type 316 stainless steel for structure (in metric tons): initial vessel, blanket, and shield, 10,000; vessel and blanket replacements; 21,000; and magnets, 19,000 —giving a total of 50,000 metric tons. At today's prices this amount of type 316 stainless steel, fabricated and field-installed, would by itself exceed the total cost of a present-day fossil-fueled or fission power plant of equivalent output.

By switching from lithium to helium as the primary coolant in the UWMAK II design (*5*), the power was increased from 1500 to 1700 MWe without a change in geometric size. A greater step toward higher power per unit size was taken with the next design, UWMAK III (*6*). Although its output was 2000 MWe, the major radius of the vessel was decreased from the 13 meters used in the earlier designs to about 8 meters, and the minor radius from an average of approximately (noncircular cross section) 5½ to 4½ meters. This smaller size permitted, for example, a reduction in the weight of structural metal in the vessel, blanket, shield, and magnets to about one-third that required in the earlier designs. The reduction in present-day cost of the structural metal would not be proportional, however, since a shift was made from type 316 stainless steel to the molybdenum alloy TZM for the reactor vessel and all hot-coolant ducting.

While the UWMAK III represents the most recently completed and cost-estimated preliminary design of a full-scale tokamak-type fusion power plant, other groups of investigators have been giving consideration to the possibilities of higher power density and more compact configurations. These invariably call for more difficult design of the magnets and the achievement of more difficult conditions in the reacting plasma. It is hoped that the feasibility of these directions can be tested in one or more of the various pilot experimental tokamak power reactors now being proposed.

Effect of Heat Removal Constraint

An aspect of fusion power complicating heat removal is that no heat transfer surfaces can be used within the reacting plasma. All of the energy released by the thermonuclear reaction must pass as heat or radiation through an envelope that surrounds the plasma region. As will be discussed later, since there are practical limits on the amount of power per unit area that can be transferred in this manner, there are then limits on the minimum physical size of the reactor that can be used for a particular plant power output.

Since reducing the size of a fusion reactor for a particular power level is an effective means of lowering the capital cost per unit output, it is important to examine the constraints on such size reductions. As power density is increased the physics of confining a plasma becomes more difficult and, for any confinement concept, a limiting practical condition will eventually be reached. For the purpose of this discussion I will assume that any required plasma conditions can be achieved. A second difficulty that is made more severe by size reduction for a particular power output is radiation damage to the vessel and adjacent components. A third difficulty is related to the problem of usefully removing the heat produced by the reactor, and this is examined in more detail in the paragraphs that follow.

For any fusion reactor employing the D-T reaction, most of the energy released will be carried into the surrounding blanket by the fast neutrons produced. This energy, plus more resulting from nuclear interactions in the blanket and shield regions, will contribute typically about 80 percent of the total heat produced. Since this heat is deposited throughout a large volume, it is not very difficult to remove by use of a circulating coolant. Unfortunately, while this heat removal feature represents an outstanding advantage of the use of the D-T reaction, the neutrons carrying the energy to the blanket are also the principal cause of the radiation damage effects that limit the operating lifetimes of the vessel and adjacent components. The balance of all of the energy released in the D-T fusion reactor, approximately 20 percent, must be absorbed by the vessel walls or be deposited in a divertor. Some designs employ a magnetic field configuration that provides paths along magnetic field lines for ions diffusing out of the plasma, and for unwanted ions that might otherwise enter the plasma, to be swept out of the reactor vessel. These ions are then guided along the field lines to a divertor collector surface where they give up their energy.

For example, the three UWMAK plants were designed (*4–6*) for a nominal power of 5000 MW thermal during "plasma burn." In UWMAK I the reactor vessel received 700 MWt (about 560 at its inner surface and 140 from internal heating), resulting in a requirement for removing an average heat flux of 0.25 MWt/m². This could be handled by the flowing lithium coolant, although magnetohydrodynamic effects resulting from interaction with the high magnetic field that was present made the problem difficult. The divertor collector, in the form of a flowing liquid lithium film within the vacuum, was estimated to receive an average heat flux of 1 MWt/m² (equivalent to 317,000 Btu's per hour per square foot). As an average heat flux into flowing lithium, this appeared manageable.

At the time of the UWMAK II design, new information indicated that a higher rate of diffusion of particles from the plasma should be expected. As a result, radiation to the inner surface of the vessel was decreased and the heating load into the divertor was increased. Including internal heat generation, the vessel heat flux averaged about 0.08 MWt/m², and the liquid surface of the divertor collector was estimated to receive an average of 3 MWt/m². The pressurized helium employed as the UWMAK II vessel coolant appeared adequate, but the same was not true of the divertor coolant. Since the charged particles swept from the plasma along magnetic field lines to the liquid metal surface could not be expected to distribute themselves uniformly over the surface provided, the University of Wisconsin group estimated that in this case a peak-to-average ratio of as much as 10 might be expected. It was pointed out that dealing in this situation with heat fluxes of up to 30 MWt/m² represented an unsolved problem.

In the UWMAK III preliminary design a similar basis for diffusion from the plasma was followed, but the plasma power density was increased to reduce the size of the reactor. A cross section of the UWMAK III torus is shown in Fig. 1. A 25-centimeter-thick graphite barrier was used near the inside surface (nearest the axis) of the torus to reduce the flux of high-energy neutrons arriving there, and thereby extend the operating lifetime of that part of the vessel. The energy deposited by the neutrons in the barrier appeared as heat, which was radiated with a nonuniform distribution to the walls of the vessel. That heat, plus some due to radiation from the plasma, plus internal heat generation in the vessel gave a total average heat flux of about 0.4 MWt/m². This heat was removed at a very high temperature (approximately 1000°C) by pressurized helium flowing in a dense pattern of TZM tubes, thereby increasing the heat removal surface area and reducing the heat flux to an effective average there of about 0.25 MWt/m² (~80,000 Btu/hour-ft²). This is slightly higher than the average heat flux that would be used in a helium-cooled graphite-moderated fission reactor power plant.

For the UWMAK III divertor collector, the lithium vapor pressure in the reactor vessel would be excessive if such a high heat flux of charged particles were deposited directly in a flowing film of the liquid metal. It was therefore decided that the divertor ion stream had to be handled differently than was done in UWMAK II. The charged particles were carried out of the high magnetic field region and made to strike a thin replaceable TZM surface cooled on the back side by flowing sodium. The calculated average heat flux was 6 MWt/m², and whether such a high value could be successfully managed is questionable. Certainly, designing for the peak conditions, which would exceed the average, would appear impossible.

It is apparent that satisfying the requirements for peak heat flux removal will be an important problem in the engineering of fusion power plants. The peak conditions will exceed the average for reasons that are inherent in the design and because of abnormal operating conditions that may occur. Both must be anticipated, and the cooling system features must be made adequate to ensure that no melting will result from transient conditions and no deleterious effects will result from excessive local temperatures over long operating periods.

Another related and important aspect of the engineering of the heat removal system is the treatment of "hot channel factors." For whatever heat removal requirement exists locally, the design must be made sufficiently conservative to meet the worst conditions that could realistically occur. Variations in manufacturing tolerances, fouling of heat transfer surfaces, inaccuracies in calculations of

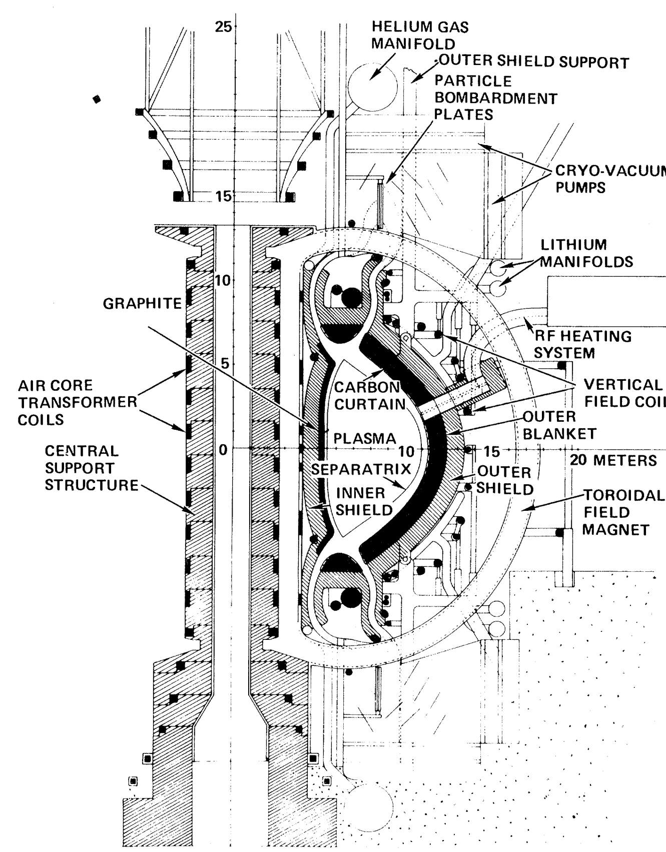

Fig. 1. Schematic cross section of the UWMAK III reactor torus.

magnetohydrodynamic effects on coolant flow, and other departures from ideal conditions will reduce the design value of the maximum coolant temperature in all coolant passages. Engineering consideration of these hot channel factors and of variations in the peak-to-average heat fluxes results in reducing the mixed-mean coolant outlet temperature. This, in turn, has a direct effect in reducing the plant power conversion efficiency and net output and in increasing the plant capital cost per unit output. None of the fusion plant preliminary designs have yet attempted to account for the effect of these considerations on plant size per unit output.

This discussion of heat removal considerations and the requirements of the UWMAK reactors illustrates the nature of the engineering problems involved. Any fusion plant employing the D-T reaction must be designed to remove a minimum of about 20 percent of the total reactor thermal power at the vessel wall and the divertor combined. (Actually, in UWMAK III, because of the effect of the partial internal barrier, the figure was approximately 27 percent.) As a practical matter, heat removal at a divertor is unlikely to permit any reduction in scale because of the difficulty of providing extended surface area for its ion collector. Regardless of the design selected, the coolant system for the vessel and any divertor must be capable of handling the peak heat flux conditions and accommodating all hot channel factors. These engineering considerations inevitably result in lowering the overall plant design performance.

If the thermal power is fixed and the reactor size is considered to be made smaller, a condition is reached where the heat removal requirement is limiting. In order to determine what minimum fusion reactor size for a particular power output is permitted by this heat removal constraint would require optimizing a design that provides for maximum and adequate peak heat removal at the vessel wall and at the divertor. While the UWMAK III heat removal system did not meet this goal, the UWMAK III power per unit size may well represent a maximum practical value. Its vessel surface area was 1600 m^2, and 20 percent of the 5000-MW thermal power would represent an average heat flux at the vessel of 0.62 MWt/m^2 (200,000 Btu/hour-ft^2), assuming no neutron barrier to add to the heat load and no power extracted by a divertor. This figure is typical of the average heat flux in the core of a pressurized-water fission power reactor.

Costs Dependent on Reactor Vessel Area

The importance of the parameter of minimum reactor vessel size for a particular power output results from the fact that the vessel area directly determines the required area of the blanket and shielding, and even determines the size of the various coils that produce the magnetic fields. These components must be external to the reactor vessel. To absorb the fast neutrons from the plasma and reduce external radiation intensities to sufficiently low levels, the blanket and shielding must be 1½ to 2 m thick. They are composed of expensive materials and depend on costly fabrication for their structure and encapsulation. As a rule, the less thick the total layers of blanket and shielding, the more expensive per unit volume are the materials of which they are made.

Again for illustration, the UWMAK I design (*4*) of blanket and shielding outside the vessel called for a 152-cm-thick structure consisting of 14 different zone layers composed of varying mixtures of stainless steel, lithium, lead, and boron carbide (Fig. 2). The UWMAK III (*6*) outer blanket and shielding regions were 194 cm thick, having nine zone layers with different fractions of stainless steel, molybdenum, lithium, graphite, alumina-silica, and boron carbide (Fig. 2). Openings through these layered structures would have to be provided (without permitting streaming of neutrons or other radiation) for the vacuum and divertor systems, equipment for fueling, instrumentation, coolant manifold, and neutral beam injectors or other equipment for plasma heating. It is also anticipated that the design would have to incorporate provision for remote access to the vessel interior for leak detection and repair. The final design will require not only large but complex structures. They will have to be field-assembled and are unlikely to lend themselves to the use of automatic welding equipment. To ensure that air will be kept out and tritium will be kept within the blanket, vacuum leak-tight welding subject to special standards and inspection techniques will be required.

It follows that any tokamak-type fusion power reactor will suffer a significant capital cost penalty because of size, complexity, and choice of materials for the vessel, blanket, shielding, and surrounding magnet coils. There are engineering restrictions on the minimum size per unit power output that will apply to these components. At some value of this parameter, heat transfer considerations will determine a limitation. Increasing the scale to permit higher plant power output will not decrease this penalty because the volumes of the components will increase in proportion to the power produced. The implication of the relationship just stated is that fusion power plants will become less competitive with other types of power plants as total output is made larger. The large cost contribution of the vessel, blanket, shielding, and magnet coils will vary approximately linearly with power output, not to some exponent less than one.

All fusion reactor concepts have the fundamental engineering disadvantage that the energy released cannot be extracted from within the plasma, but must be collected by some means at the periphery of the reacting volume. This disadvantage might not be so serious were it not for the fact that for technical reasons the minimum periphery represents a sizable area per unit power output and requires a large capital investment per unit area. This is quite in contrast to power plants based on the combustion of fossil fuels or the nuclear fission process. In both fossil-fueled furnaces and fission reactors, heat can be extracted from within the reacting volume and the cost of the boiler tubing or fuel element cladding per unit area is small. In comparison, the heat transfer surface per unit area represented by the vacuum vessel in a fusion reactor is extremely expensive. As described above, every square meter of such a surface in a reactor based on the D-T reaction requires 1½ to 2 m^3 of expensive materials.

Capital Cost Estimates

The preceding paragraphs gave qualitative reasons why the capital cost of a fusion plant, particularly the nuclear island, will be high. A more quantitative argument was presented in an earlier paper (*7*) in which the cost of a tokamak-type fusion power plant was estimated. As an example the UWMAK I vessel, blanket, shield, and magnet design was used, but the volume enclosed by each of these components was reduced to correspond to the reactor vessel size with the thermal power output of the UWMAK III. This is a favorable case in that the choice of materials and component thicknesses in the UWMAK I comprises a low-cost design, and the thermal power-to-size ratio of the UWMAK III represents what was just described as a practical maximum based on heat transfer considerations.

The estimate was based on unit costs for large-scale procurement and field installation to required standards typical of current nuclear industry equivalent experience. Other direct and indirect costs were based on the UWMAK III estimate prepared by the University of Wisconsin group and the Bechtel Corporation (*6*). The result was a total estimated cost (first-quarter 1977 dollars) of \$8590 million for a plant with an average design output of 1750 MWe (*7*). Contingency and interest during construction, but no escalation or special owner costs, were included. Also, the cost of replacements for the vessel and adjacent components over the life of the plant was not included. The plant was assumed to be a first-generation one but not the first of its kind constructed.

A revised estimate for the same fusion power plant has been subsequently prepared with the benefit of more detailed costs for the liquid-metal heat transfer system, steam generator, turbine generator, and entire power conversion installation compiled for the prototype liquid-metal fast breeder reactor (LMFBR) plant (*8*). These costs were scaled according to the 0.7 power of the ratio of electrical outputs (1750 MWe divided by 1000 MWe for the LMFBR). Similarly, the indirect costs were revised by scaling those from the UWMAK III estimate according to the 0.7 power of the ratio of total direct costs (the new direct cost figure divided by the UWMAK III direct cost estimate). These indirect costs include construction facilities and services as well as engineering services. The result, after adding in contingency and interest during construction on the same percentage basis as in the earlier estimate, was a total construction cost of \$7780 million.

This revised total cost estimate is equivalent to \$4450/kWe. Neglecting operating and maintenance costs, the electrical energy produced would cost 10.8¢/kWh, assuming a plant factor of 0.8 and charges of 17 percent per year against the capital investment. For comparison, capital costs for coal-fueled plants with stack gas desulfurization and for light-water fission reactor plants are \$780 and \$975/kWe, respectively (*7*). While variations in location, plant size, and other special factors result in a range of capital costs, these figures are typical for plants ordered, assuming 1977 dollars without escalation or special owner costs.

A comparison can also be made with the capital cost of an LMFBR plant, using the recent design study for a 1000-MWe prototype station (*8*). Including a 30 percent contingency and an average interest of 8 percent per year for 3 years during construction, which were employed in the fusion plant estimates, gives a total construction cost of \$1820/kWe for the LMFBR. In view of the relative status of fusion and fission breeder technologies, use of the same contingency factor should weight the comparison in favor of the fusion plant.

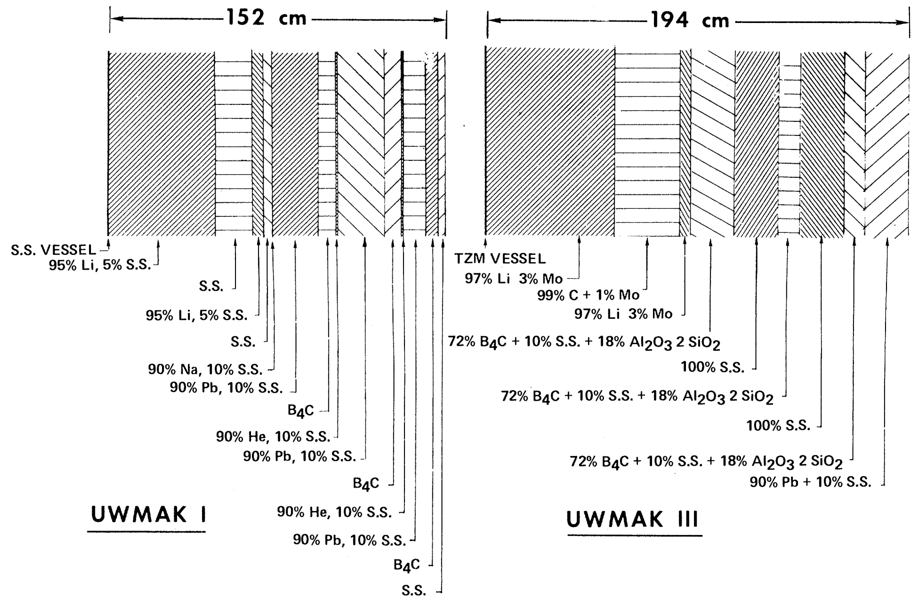

Fig. 2. Materials and their thicknesses comprising the blanket and shield regions surrounding the reactor vessels in the UWMAK I and UWMAK III designs.

Limitations Imposed by Radiation Damage

The second problem area regarded as critical to any successful application of fusion power is related to the integrity of the reactor vessel. There are a number of difficult engineering requirements which this component must satisfy. The vessel must maintain vacuum tightness, operate at elevated temperature, withstand repeated thermal cycles and stresses from external pressure and nonuniform temperature distributions, be corrosion-resistant to the primary coolant and its impurities, retain adequate mechanical properties and dimensional stability while subjected to intense radiation, be capable of field fabrication, and be available in large quantity at an economic price. While each of these performance demands limits the design choices, the most serious requirement is that the vessel retain adequate mechanical properties in spite of the effects of a high fluence (time-integrated flux) of energetic neutrons.

The principal difficulties caused by the high-energy neutron interactions are loss of ductility and swelling in the vessel material. These effects are sufficiently serious that all engineering studies of fusion power plant designs based on the D-T reaction have concluded that periodic replacement of the reactor vessel would be required. Some recent experimental results (*9*) have indicated that the frequency of replacement could be reduced by using cold-worked type 316 stainless steel and operating at a maximum temperature of 300°C. It is possible that a total fast neutron fluence equivalent to 20 MW-year/m^2 could be achieved with such a design. Unfortunately, the need to keep the reactor size as small as possible for a particular power level, to minimize capital costs, results in an intense neutron flux. For example, the UWMAK III thermal power level and size would give rise to an average fast neutron flux of 2 MW/m^2. Designing for a lower maximum vessel wall temperature also has the disadvantage of reducing the plant electrical output.

It is a basic difficulty of the fusion concept that the component that must meet the most stringent design conditions, the reactor vessel, is necessarily the component that is subjected to the most intense damaging radiation. Its replacement is made difficult because the induced radioactivity requires the use of remote means. This difficulty is made more extreme by the fact that the vessel is necessarily designed into the systems for heat removal, vacuum pumping, fueling, plasma heating, and other functions. Furthermore, the vessel is almost inaccessible because it must be completely enclosed by a sufficient thickness of neutron-absorbing blanket and radiation shielding. And, in a tokamak configuration, it is further enclosed within a set of surrounding and interlocking magnet coils.

Possibilities of Other Fusion Reactions and Confinement Methods

Since any use of the D-T fusion reaction is accompanied by certain major difficulties, such as the requirement to breed tritium and the inherent high radiation damage rates, the question of the possibility of employing other fusion reactions invariably arises. Investigators studying this prospect are generally agreed that the tokamak-type reactor is probably incapable of achieving the necessary plasma conditions for any other fusion process. The next least difficult fusion reaction would be D-D. While it would entail no requirement for breeding, there would still be a significant production of high-energy neutrons from the plasma. The limitation that heat removal by the combination of vessel and divertor places on minimum reactor size would be more severe. With the D-D reaction, approximately 60 percent rather than 20 percent of the total thermal power would have to be removed there. Other advanced fusion fuel cycles are not considered feasible with the tokamak-type reactor.

Although this discussion of engineering aspects of possible future fusion power plants has been directed to the use of the tokamak concept, many other approaches to the controlled thermonuclear reactor are being investigated. They include methods based on other magnetic plasma confinement schemes and on concepts dependent on inertial confinement. If the fusion reaction employed is to be D-T, essentially all of the foregoing discussion on engineering problems still applies. The effect of radiation damage in limiting the operating lifetime of the reactor vessel and its adjacent components would be present. A minimum vessel size per unit power output would be established by heat transfer limitations, and a significant plant capital cost would be contributed by the volume of vessel, blanket, and shielding. Inertial confinement methods can avoid the expense of surrounding magnet coils, but they would have their own special equipment, such as a high-power laser system, to provide for pellet heating.

Next, we must ask whether one of these alternative plasma confinement methods might permit the use of an advanced fuel cycle that would avoid the engineering problems inherent in the D-T and even the D-D fusion reactions. It is true that some of the proposed fusion fuel cycles, particularly any based on reactions producing only charged particles, could avoid the fast neutron radiation damage problem. The requirement for a breeding blanket might be removed, and the thickness of the surrounding shielding could be reduced. Such fusion reactions, however, aggravate the problem of minimum reactor vessel size per unit power output. A reaction involving only charged particles requires that 100 percent of the thermal power be extracted at the vessel wall and the divertor, if one is employed, by coolants capable of removing whatever peak heat fluxes occur at those locations.

To carry this sequence of possibilities one step further, schemes have been suggested for removing the power of the fusion reaction by directly converting the kinetic energy of the plasma charged particles into electrical energy, rather than by extracting heat radiated in some form from the plasma. Such an approach would obviously avoid the limitation on minimum reactor vessel size per unit power output imposed by heat transfer considerations. However, the requirement that the energy released by the fusion reaction must serve to maintain the plasma at a high temperature, where an appreciable fraction of power will then be radiated, makes this concept unlikely to be practical. Also of unlikely practicality is another suggestion that a plasma could be maintained at such an extremely high temperature that the radiation would appear as x-rays capable of penetrating the reactor vessel wall and depositing within some high-density flowing coolant, which then would not be subject to surface heat transfer limitations.

Conclusions

The importance of reducing the construction cost of fusion plants through reductions in reactor size for a particular power output has been discussed. It was pointed out that a minimum size limitation is set by the need to remove the heat produced, and that this would result in a minimum volume of expensive construction materials. This is a consequence of a fundamental engineering disadvantage of the fusion power concept, in which all energy must be gathered outside the reacting plasma region and the required area of surrounding surface must have associated with it a thick structure of complex design.

The real significance of the capital investment required for the nuclear island will become more apparent as further engineering studies of fusion plant designs are carried out and cost estimates for the necessary fabrication and field erection are based on more recent procurement experience in the nuclear industry. In the example presented here, although the assumptions related to the fusion plant were favorable, the comparison with fossil-fueled and fission reactor plants indicated that the electrical energy produced would be noncompetitive.

Regarding the other critical problem area, it was pointed out that there is still no structural material and operating condition that will ensure a lifetime for the reactor vessel that will match that of the plant. Although all the proposed designs have suggested periodic replacement of the vessel, the associated costs and shutdown time will probably make this an unacceptable operating requirement for utilities.

Most of the discussion was directed to the tokamak magnetic confinement reactor operating on D-T fuel, but the arguments related to costs were for the most part applicable to other confinement methods and other fuels. The radiation damage limitation on the reactor vessel would apply only to the use of thermonuclear reactions producing high fluxes of energetic neutrons.

It must be concluded that any future commercial application of fusion power is faced with two serious engineering limitations. Present information indicates that even for future optimum plant designs, the magnitude of the required capital investment is likely to lead to a noncompetitive cost for the power produced. In addition, the operational limitation resulting from the deleterious effects of radiation on the reactor vessel remains an obstacle to the successful application of the D-T fusion reaction.

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