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NEW DIRECTIONS IN FUSION MACHINES:
REPORT ON THE MFAC PANEL X ON HIGH POWER DENSITY OPTIONS[*]

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Abstract: The high cost of fusion is motivating a shift in research interest toward smaller, lower-cost systems. Panel X of the Magnetic Fusion Advisory Committee (MFAC) was charged to assess the potential benefits and problems associated with small, high-power-density approaches to fusion. The Panel identified figures of merit which are useful in evaluating various approaches to reduce the development costs and capital costs of fusion systems. As a result of their deliberations, the Panel recommended that "...increased emphasis should be given to improving the mass power density of fusion systems, aiming at a minimum target of 100 kWe/tonne", and that "Increased emphasis should be given to concepts that offer the potential to reduce substantially the cost of development steps in physics and technology."

1. INTRODUCTION

1.1 Interest in New Directions

The emphasis of fusion research in the United States has been moving toward smaller, lower-cost systems because of the high development and capital costs projected for fusion systems based on the present main-line concepts. The shift in emphasis is exemplified by the increased interest in higher beta tokamaks and stellarators, smaller more efficient end plugs for mirrors, and compact alternate concepts such as the reversed field pinch (RFP), compact toroids (CTs), and the dense Z-pinch. The Department of Energy (DOE) requested that the Magnetic Fusion Advisory Committee (MFAC) assess the potential benefits and problems associated with these smaller systems and with high-power-density fusion systems in general.

1.2 MFAC Panel X

The charge letter[**] from A. W. Trivelpiece, Director of the Office of Energy Research (DOE), to the MFAC Chairman, R. C. Davidson (MIT) was presented during the MFAC meeting on May 1-2, 1984. During that meeting, the MFAC organized Panel X, chaired by Professor Robert W. Conn (UCLA), to respond to the charge. The other 15 members of the Panel represented all facets of the fusion program: Robert A. Gross (Columbia U.), Mohamed Abdou (UCLA), Charles C. Baker (ANL), Lee A. Berry (ORNL), Donald Dobrott (SAIC), Harold P. Furth (PPPL), James D. Gordon (TRW), Robert A. Krakowski (LANL), Nicholas A. Krall (JAYCOR), Rulon K. Linford (LANL), B. Grant Logan (LLNL), Peter H. Rose (MSNW), Ramy Shanny (Consultant), Taruo Tamano (GA Tech), and Shoichi Yoshikawa (PPPL).

The Panel met four times during the following year, and invited experts from national laboratories, industry, and universities to give presentations covering the broad variety of topics associated with the charge to the Panel. Subgroups of the Panel met or interacted more often to resolve issues and write conclusions which were subsequently shared with and revised by the entire Panel. The final Panel X Report[**] was presented to the MFAC during the May 8-9, 1985 meeting. The Report was accepted by MFAC and transmitted to A. W. Trivelpiece along with a transmittal letter[**] which comments on several points associated with the Report.

1.3 Charge to Panel X

The charge letter can be summarized by two central questions:

1. What are the potential benefits and problems of high-power-density fusion systems compared with medium-power-density systems?
2. In light of this comparison what should the relative research emphasis be on high-power-density systems in the national fusion program?

The letter also requested information on several specific topics including the impact of high power density on the cost of electricity (COE), capital costs, and subsequent expenses (operating, availability, decommissioning, etc.) associated with a fusion reactor, as well as the cost, path, and timescale for the development of fusion. It asked for an assessment of the impact of safety, environmental, and engineering issues on the development of high power density reactors, and of the technological developments that would be required. Moreover, the suitability of the various confinement concepts to achieve high power density was to be assessed, including the credible range of improvements that could be expected and the identification of promising confinement concepts not being developed by DOE.

2. FIGURES OF MERIT

2.1 Purpose and Limitations of Figures of Merit

The Panel found it necessary to select figures of merit to aid in the comparison between various confinement concepts and reactor approaches. These figures of merit were found useful if caution were exercised; the effects of many important details and complexities are not automatically included in comparisons based on these simple figures of merit. If properly used, these simple parameters can help identify general trends which must be substantiated by more detailed studies.

2.2 Selected Figures of Merit

Figures of merit were selected by the Panel to "measure" the system size, power density, magnetic field utilization, plasma energy confinement, and plant efficiency. The choices are not unique and better choices may be possible, but the Panel found them to be useful. Some comments on the reasons for the choices and on the inherent limitations follow.

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[*] Work performed under the auspices of the U.S. DOE.

[**] Copies of the charge letter, Panel X Report, and the MFAC transmittal letter can be obtained from R. C. Davidson, Director, Plasma Fusion Center, MIT, NW16-202, 167 Albany Street, Cambridge, MA 02139.

- 2.2.1 System Size. The two "size" parameters that appear to be easily linked to economic factors are the net electric power or unit power (P_e in MWe) which is sold to the customer, and the mass of the fusion power core (M_{FPC} in tonne) which is related to the capital cost of the fusion power core (FPC).

The FPC, as shown in Fig. 1, was defined by the Panel to exclude the auxiliary systems as well as the balance of plant (BOP). Substantial discussion occurred over whether to include the auxiliary systems in the FPC. The arguments for including the auxiliaries are: The auxiliary systems are determined by the characteristics of the type of fusion confinement system being used, and the capital cost of the auxiliaries can be substantial, even larger than the cost of the FPC for some concepts. The arguments for excluding the auxiliaries are: The mass and cost of the auxiliaries are not easily or accurately determined from basic characteristics of a confinement concept; more detailed information about the confinement concept and specific reactor design are needed to estimate the cost of the auxiliaries than are needed to estimate the cost of the FPC as defined in Fig. 1. It was considered more important to have a readily determined measure of the irreducible mass (cost) associated with a concept than to include more of the mass (cost) and lose simplicity and, probably, accuracy in the process. If a reasonably accurate method for estimating the mass or cost of auxiliaries could be devised, without having to resort to a conceptual reactor design, then an improved figure of merit would result.

2.2.2 Power Density. The ratio of the unit power (P_e) to the mass of the fusion power core (M_{FPC}) was selected to measure the power density, and was named the mass power density (P_m in kWe/tonne). Because P_m depends on M_{FPC}, the limitations and features described in the previous section apply to P_m.

Care must be used in evaluating and using both M_{FPC} and P_m. For example if copper magnets are replaced by aluminum magnets, M_{FPC} and P_m are affected substantially but capital cost is not. Nevertheless, M_{FPC} and P_m remain useful in comparing concepts where the assumptions are kept constant. To make these comparisons more meaningful the Panel adopted some guidelines on what to include in M_{FPC} and P_m; e.g. only the shielding needed to protect the magnets is included even though additional biological shielding may be located in the same vicinity. Some choices are harder to make and remain unresolved; e.g. should the mass of a liquid breeder/coolant be included? In summary, M_{FPC} and P_m are useful figures of merit if used properly, but improvements and clarifications can probably be made.

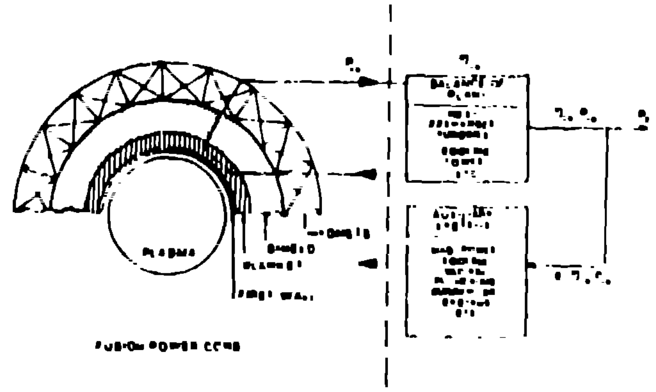

Fig. 1. Fusion reactor schematic showing the relation between the fusion power core (FPC), auxiliary systems, and the balance of plant (BOP).

2.2.3 Magnetic Field Usage. The efficiency with which the magnet-generated field is used to support the plasma pressure necessary for fusion is indicated by the engineering beta (β_e in percent), which is defined as the ratio of plasma pressure averaged over the plasma volume to the magnetic field pressure averaged over the inner surfaces of all the magnet coils $\langle B^2_{coil} \rangle$. The value of β_e should be inversely correlated with the cost* of the magnets needed to confine the plasma.

2.2.4 Plasma Energy Confinement. The Panel selected the average thermal diffusivity (χ_E in m²/s) to quantify the loss of energy from the plasma. Neglecting radiation (and axial losses from tandem mirrors)

$$\chi_E = a^2/4\tau_E \quad , \tag{1}$$

where a is the minor radius of the plasma and τ_E is the energy confinement time. To account for axial losses, Eq. (1) can be used to define an effective χ_E for tandem mirrors. The value of χ_E is correlated to the size of the plasma chamber (see Fig. 1) required to confine an ignited or fusion-grade plasma.

2.2.5 Efficiency. Two important efficiencies for a reactor system (see Fig. 1) are the thermal conversion efficiency η_{th} which is the efficiency of converting the thermal power, P_{th}, from the FP to electric power, and the recirculating power fraction, ϵ_r, which is the fraction of the electric power which must be used to run the reactor. It is obvious from Fig. 1 that the unit power or net electric power is given by

$$P_e = \eta_{th} (1-\epsilon_r) P_{th} \quad . \tag{2}$$

3. METHODS FOR REDUCING THE COST OF FUSION

3.1 Factors Affecting the Cost of Electricity (COE)

Figure 2 shows some of the factors and relationships that determine the COE. Safety and environmental factors affect all of the direct contributions to the COE. The overall cost impact of safety and environmental factors is difficult to quantify, but some trends will be described during the discussion of the direct contributions. Fuel costs for fusion systems should not be significant, unlike those for fossil and fission systems. Operating costs could be significant but not dominant. The complexity of fusion systems will tend to increase the operating costs, but the impact of safety on these costs should be comparable to or less than fission.

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* A definition for β_e has been recently proposed by B. G. Logan (a member of the Panel) which might improve this correlation, i.e. the ratio of the total plasma energy to the total field energy supplied by the magnets.

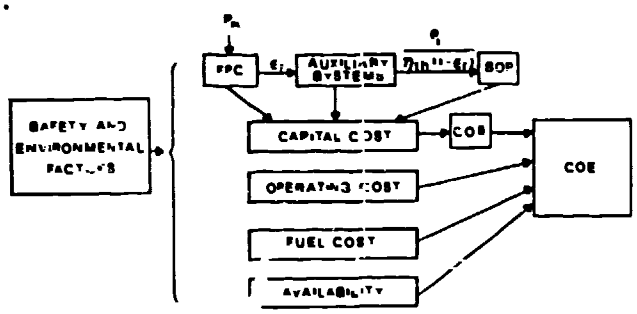

Fig. 2. Relationships between some of the figures of merit and other factors that affect the cost of electricity (COE).

Availability is a major factor in determining COE. However, we must wait for the engineering development phase for fusion before we can generate the data needed to estimate the availability of a given reactor design. Nevertheless, certain trends are obvious. Complexity and high stresses will tend to decrease the mean-time-to-failure; simplicity and small size tend to facilitate rapid replacement. Although some attempt is made in reactor studies to quantify these kinds of effects, the models are not very satisfying because of the lack of relevant data.

The major costing effort of reactor studies is focused on capital costs. Next to availability, capital costs, along with the cost of borrowing money, COB, for the capital, are the major contributors to the COE. The remainder of this Section 3.1 is devoted to the factors which affect these capital and financing costs.

3.1.1 Efficiency and Complexity. The level of technology and complexity is a major factor in the capital costs of the FPC and auxiliary systems. Neutral-beam and rf heaters and current-drive systems are examples of high-technology cost drivers in the auxiliary system category. Decreasing the complexity of items such as magnet and divertor systems can decrease the cost of the FPC.

The capital cost of the auxiliaries is also affected by the recirculating-power fraction, ϵ_r (see Figs. 1 and 2). The less power required for auxiliaries (e.g., for current drive or for losses in resistive magnets) the smaller the cost of the auxiliaries. In addition, a decrease in ϵ_r decreases the thermal power, P_{th}, handled by the balance of plant (BOP) for a given unit power, P_e (see Eq. (2) and Fig. 2). The result is a decreased capital cost for the BOP.

The BOP cost can also be reduced by increasing the thermal conversion efficiency, η_{th}. Usually the conversion involves conventional thermal cycles. If a large fraction of the fusion power could be converted by more efficient nonthermal processes, significant BOP cost savings might result.

3.1.2 Mass Power Density, P_m. Increasing P_m for a given P_e should reduce the capital cost of the FPC. However, reactor studies indicate that a threshold value of P_m exists, beyond which very little reduction in COE is realized with further increases in P_m. This effect is clearly shown in Fig. 3. This threshold corresponds to the value of P_m beyond which the capital cost of the FPC (see Fig. 2) becomes insignificant compared with the capital costs of the auxiliary systems and BOP. In fact, large increases of P_m beyond the threshold can cause ϵ_r, and hence COE, to increase. This effect is evident for the 500-MWe curve in Fig. 3. Thus present models for estimating COE do motivate the increase of P_m to the threshold value, but not much beyond.

Other factors motivate the achievement of P_m values higher than the threshold. Some increase would provide a safety margin to accomodate uncertainties in present estimations of reactor characteristics and costing. The potential for factory fabrication and assembly of the FPC, described next, provides another motivation for higher P_m.

3.1.3 Factory Fabrication of the FPC. The Panel heard from members of the fission community about the potential benefits of having the reactor core fabricated and assembled in a factory. Similar benefits for fusion could occur if the mass of the FPC could be reduced sufficiently (to about 1000 tonne) to allow factory assembly and shipment to the site. The standardization and quality control provided by the factory would not only reduce fabrication costs but could substantially reduce the licensing time and, therefore, the financing costs. Moreover, the improved quality control should increase the availability of the plant.

Since the mass of the FPC in most reactor projections for the 1000-MWe class is more than 10,000 tonne, substantial reductions would be required. However, some concepts have the potential of achieving small sizes, and the benefits could be substantial. These factors are not included in present costing models.

3.1.4 Unit Power, P_e. The economy of scale, evident in Fig. 3, motivates the use of large P_e. However, increases of P_e much beyond 1000 MWe do not result in much reduction of COE. For this reason most reactor studies are done for P_e ~ 1000 MWe.

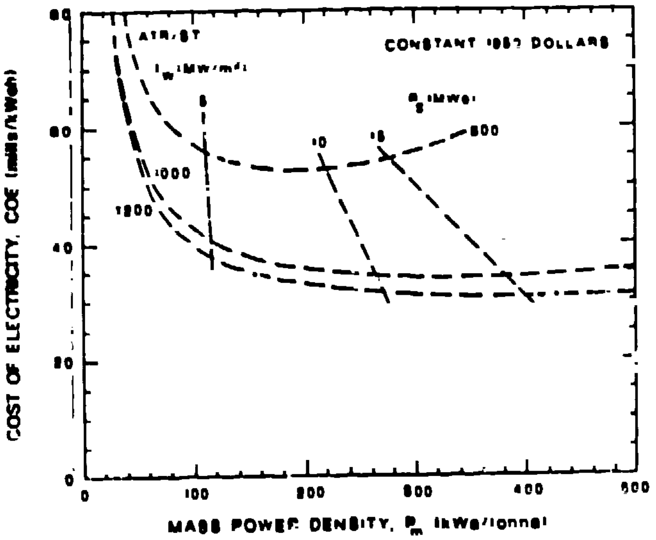

Fig. 3. COE vs P_m for a Spherical Torus[1] producing 500, 1000, and 1200 MW_e net electric power.[2] Curves of constant neutron wall loading are also shown.

However, the Panel learned from the fission industry reasons for reducing P_e below 1000 MWe. Smaller P_e (200 to 600 MWe) units with high P_m may be the only way to achieve small enough FPC mass to allow factory assembly and shipment to the site. The previously described cost savings associated with factory fabrication would mitigate the economy of scale. Some of the benefits of scale could be retained by building up a 1200 MWe-plant, for example, with 4 factory-fabricated 250-MWe units. By phasing the installation of the units, the utility could minimize the initial capital investment, reduce the time delay between investment and return-on-investment, and match the growing plant capacity with the demand for electric power. All of these advantages would greatly reduce if not overcome the economy of scale for the P_e range of a few hundred MWe.

3.1.5. Safety and Environment. The members of the fission community that advocated factory fabrication also stressed the importance of a passively safe design, i.e., no active safety system or procedure is needed to prevent radiation release caused by radioactive afterheat induced core damage (e.g., melt down) in the case of a loss-of-coolant accident. In addition to the obvious potential advantage of improved public acceptance, passively safe units offer potential savings in capital and operating costs. The savings accrue from eliminating the safety systems, such as emergency cooling systems, and from reducing the fraction of the plant under the nuclear stamp, thereby reducing construction costs. These savings need to be compared with possible increases in the cost of the unit to make it passively safe. In the case of fission, substantial net savings are predicted.

Compared with fission, the damage or melt down of a fusion blanket is likely to be much less of a public safety hazard. Nevertheless, passively safe fusion systems should be studied for reasons of safety and public acceptance as well as for potential cost savings. A simple way to achieve passive safety in a fusion blanket is to limit the neutron wall loading. This restriction in turn imposes concept-dependent limits on the maximum P_m that can be achieved. Thus passive safety is one of the considerations in determining optimum values for wall loading and P_m.

Tritium handling and remote maintenance are two factors that will have a significant impact on capital costs as well as costs and availability. If the FPC were a small factory fabricated unit, the most practical maintenance procedure might be to replace the entire FPC rather than replacing FPC components. Substantial capital could be saved by not requiring each plant to have the complex remote handling capability of replacing a variety of components. A single factory could supply and repair the small standardized FPCs for many plants.

Another factor which must be considered is radioactive waste disposal. Environmental and economic factors are important in selecting materials. Near surface burial would be desirable.

3.2 Factors Affecting the Development Costs

The "development" phase for fusion was defined by the Panel as the steps in the program between an ignition experiment and a commercial plant. The economic impact of availability on the development process will increase substantially from the ignition experiment to the commercial plant. Moreover, important data will be collected that will allow this impact to be better understood and predicted.

In contrast, capital costs are of major importance at every step of the development phase. Thus efficiency, complexity, P_m, safety, and environment are also important economic factors for the entire development phase as they are for commercial systems*. In addition, the economy of scale for unit power, P_e (or the associated thermal power, P_{th}), is unimportant in the development phase except for the last step(s) before the commercial plant. Thus concepts which allow low P_e (P_{th}) with large P_m could reduce the mass and cost of the fusion power core (FPC), auxiliary systems, and balance of plant (BOP). The corresponding reduction in development cost, schedule, and risk could substantially facilitate the development of fusion.

The next two subsections examine the methods for achieving high P_m and low P_e within the constraints associated with efficiency, complexity, technology, safety, and environment.

3.3 Approaches for Increasing Mass Power Density, P_m.

Simple geometrical arguments indicate that two independent approaches for increasing P_m are to either increase the average wall loading, or to decrease the radial thickness of the fusion power core (first wall, blanket shield, and magnet as shown in Fig. 1) while holding ε_r constant.

3.3.1 Increase the Average Neutron Wall Loading, $\langle I_w \rangle$. Increasing $\langle I_w \rangle$ not only increases P_m, but also increases cooling requirements, thermal stress, neutron damage rates, and afterheat power density in the blanket. These technological and safety issues tend to impose practical limits to the magnitude of $\langle I_w \rangle$. The Panel found that 5-10 MW/m^2 was likely to be the optimum range for $\langle I_w \rangle$ in reactors with standard structural walls.

It can be shown that

$$\langle I_w \rangle \propto \beta_e^2 \langle B_{coil}^2 \rangle^2 a \quad , \qquad (3)$$

where β_e and B_{coil} are defined in Section 2.2.3, and a is the radius of the plasma. Equation (3) indicates that increasing β_e is always beneficial. If $\langle I_w \rangle$ is less than the optimum range, then increasing β_e allows P_m to increase. Once the optimum range of $\langle I_w \rangle$ is reached, a further increase in β_e would allow B_{coil} to be decreased which decreases the FPC thickness. This is the second way of increasing P_m.

3.3.2 Decreasing the FPC Thickness, Δ. One method of decreasing Δ has just been described. Other examples include better magnet designs that would allow either thinner magnets (higher current density) or less shielding. Blanket thickness might be reduced by more efficient breeding techniques. However, a very significant decrease in Δ occurs when β_e is sufficiently high to allow the superconducting coils to be replaced by resistive (e.g., copper) coils of similar thickness, without a significant increase in ε_r. This change to resistive coils allows the virtual elimination of the shield with a corresponding decrease in Δ.

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* For those steps in the development phase where the thermal power is not converted to electricity, an effective P_m can be calculated by using Eq. (2), the effective ε_r, and an assumed η_{th} (~1/3).

TABLE I

CONCEPT CLASSIFICATION

	TFD	PFD
Dominant confining field	Toroidal (Axial)	Poloidal
Supported mainly by currents in:	Magnets	Plasma
Examples	Tokamak Stellarator EBT (Tandem Mirror)	RFP Spheromak FRC Dense Z Pinch
Naturally excels in:	Low χ_E (across field)	High β_e

The high values of β_e that are required for this change to resistive coils and the corresponding increase in P_m do not appear to be equally accessible by all confinement concepts. Table I compares characteristics of toroidal-field-dominated (TFD) and poloidal-field-dominated (PFD) systems. The externally imposed magnetic field in TFD concepts provides good confinement (low χ_E) for even modest experiments. However, this strong reliance on magnets makes the achievement of high β_e more difficult. In fact all TFD concepts rely on neutral beam or rf auxiliary heaters to increase β_e and to reach ignition.

In contrast, the reliance on internal plasma currents to provide the confining fields in PFD concepts results in comparatively poor confinement for modest (low-current) experiments, but the β_e is high. Moreover, the high plasma currents are expected to allow all known PFD concepts, except for the (FRC), to reach ignition by ohmic heating alone. Since auxiliary heaters are not needed, the complexity and the capital cost of the auxiliaries are reduced. The high β_e and lower ε_r make high P_m more accessible because the transition from superconducting to resistive coils at a given P_e is more accessible. The realization of this natural potential for high P_m depends on achieving improved confinement (decreased χ_E).

These observations about TFD and PFD concepts resulted in one of the findings in the Panel X Report.

> Finding 3: Concepts that confine high-β plasmas (β > 10%) with magnetic fields produced mainly by currents within the plasma are more naturally consistent with high mass power density. This general principle is most quantitatively demonstrated for the Reversed Field Pinch (RFP). The Spheromak, FRC, and Dense Z-Pinch have the appropriate characteristics.

3.4 Approaches for Decreasing the Unit Power, P_e

The benefits derived from reductions in P_e are dependent on simultaneously achieving or maintaining high P_m. Two independent paths for decreasing P_e are to either decrease $\langle I_w \rangle$, or to decrease the plasma size.

3.4.1 Decrease Average Neutron Wall Loading, $\langle I_w \rangle$. This approach is not allowed because it results in decreased P_m (see Section 3.3.1).

3.4.2 Decrease Plasma Size, r_p. The plasma size can be decreased in two ways without decreasing P_m. The plasma length or aspect ratio could be reduced if other physics and technology constraints would allow it, or the plasma radius r_p could be reduced if β_e could be correspondingly increased to maintain constant $\langle I_w \rangle$ (see Eq. (3)) and hence constant P_m. Note that increasing B_{coil} is not allowed because it would cause an increase in ε (see Section 3.3.2) and hence in P_m. The decrease in r_p also requires improved confinement, i.e., a decrease in χ_E. Thus, in order to have the flexibility to both increase P_m and decrease P_e, the two key goals for plasma confinement research are high β_e and low χ_E.

4. CENTRAL RECOMMENDATIONS OF PANEL X

4.1 The Target of High Power Density.

The methods described above for reducing the cost of fusion are coupled in a complex fashion through constraints imposed by physics, technology, safety, and environmental factors. These complexities, added to the lack of data in several important areas, lead to substantial uncertainties in estimating development costs or the COE for reactors. In spite of these uncertainties, certain trends are still apparent, and some of these trends have been mentioned in this paper. Cognizant of both trends and uncertainties, the Panel agreed on 27 findings, 13 recommendations, and 2 central recommendations. The first central recommendation states:

Central Recommendation #1

> In setting fusion program priorities, increased emphasis should be given to improving the mass power density of fusion systems, aiming at a minimum target of 100 kWe/tonne. The increased emphasis should be applied to all aspects of the fusion program, including confinement research, fusion reactor design and system studies, and technology research and development.

The minimum target of $P_m \approx 100$ kWe/tonne was obtained from examining a number of both parametric and point reactor studies for a variety of concepts. The threshold value of P_m was found to be 100 kWe/tonne, i.e., below this value the COE rises sharply while above it little change in COE is observed. This effect has been confirmed again in a more recent reactor study[2] as shown in Fig. 3. The uncertainties in estimating COE motivate the achievement of P_m values even higher than this threshold value.

A comparison of P_m values for a variety of reactor designs is shown in Fig. , taken from the Panel X Report. Note the progress toward the threshold of high mass power density that has been made by the tokamak designs. Higher β_e (corresponding to $\langle\beta\rangle$ > 10%) is expected to result in tokamak designs that reach or moderately exceed the target P_m. Recent tandem mirror designs with smaller endplugs have reached the target value. The Panel agreed that credible improvements could allow all of the confinement concepts considered to at least reach the target P_m.

The tendency for PFD concepts to achieve higher P_m than TFD concepts (see Table I) is also evident in Figure 4. In fact the PFD concepts are competitive with the PWR fission core. The only "exception which proves the rule" is the Riggatron. This tokamak design assumes a very high β (~ 25%) for a tokamak and accepts a very high neutron wall loading (30-45 MW/m^2), and high recirculating power fraction (ε_r ~0.4). In contrast the CRFPR(5) design assumes a poloidal β = 20%

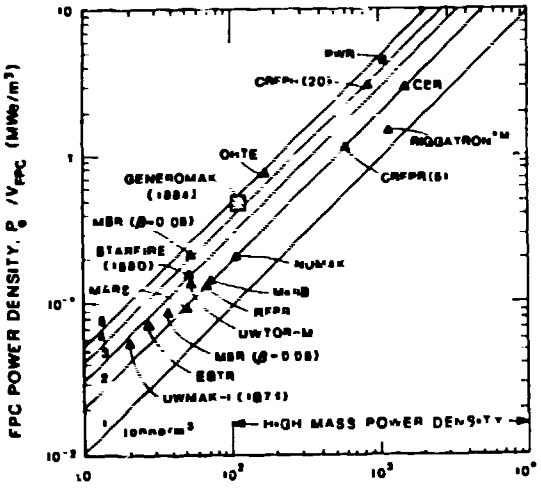

Fig. 4. Comparison of power densities projected by reactor studies. Diagonal lines are contours of constant average mass density of the fusion power core. Several confinement concepts are represented. Tokamak: UWMAK-1, UWTOR-M, STARFIRE, MKIIB, NUMAK, and RIGGATRON. Tandem mirror: MARS. EBT: EBTR. Stellarator: MSR. General toroidal superconducting study: GENEROMAK. OHTE: OHTE. Reversed field pinch (RFP): CRFPR. Spheromak: CSR. Pressurized water reactor (fission): PWR.

which has already been achieved in RFPs, a modest neutron wall loading of 5 MW/m², and reasonable ε_r = 0.22. The high values of P_m projected for PFD concepts not only provide a substantial safety factor to accomodate uncertainties in projecting COE costs, but also offer the potential of factory fabrication, single piece maintenance, and the associated benefits.

4.2 Development Path

No generally accepted model or framework exists for planning the development phase, i.e., the steps between the ignition experiment and a commercial plant. The number of steps, the schedule, and the cost depend on the level of risk that is deemed acceptable. In this uncertain situation, estimates of total cost and timescale for development are not very useful. However, the factors which affect the capital cost of each step in the development process can provide useful guidance, as discussed in Section 3.2. These observations contributed to the second central recommendation.

Central Recommendation #2

Increased emphasis should be given to concepts that offer the potential to reduce substantially the cost of development steps in physics and technology. These steps include physics development in ignition and reactor-relevant burn conditions, and technology development at reactor-relevant neutron wall loading. The feature of a concept that is expected to result in reduced cost for developmental steps is a low fusion power coupled to a low fusion-power-core mass. The Panel recommends establishing a methodology to evaluate pathways and costs for fusion power development.

5. OBSERVATIONS OF THE AUTHOR

5.1 Significance of Panel X Report

Most reactor studies assess the potential benefits and problems of a particular fusion concept, or a fairly narrow class of concepts, by analyzing the integrated set of factors associated with physics, technology, economics, environment, and safety. These studies have proved valuable by identifying problems and solutions, and by providing information which is important in setting priorities and research directions. The Panel X Report is an analysis of the information collected and integrated from a number of reactor studies covering a wide spectrum of concepts. The Report identifies techniques for making comparisons between concepts and approaches. These techniques are important in assessing potential benefits and problems and in identifying those which were concept specific and those which appear to be generic for magnetic fusion. I believe that the Report is important for the entire fusion program for the same reasons that reactor studies are important for the concepts being studied.

The issues in the Report are numerous and the interrelationships are complicated. I have only been able to deal with a small fraction of them in this brief paper. Nevertheless it is important for the members of the fusion community to understand the issues and arguments described throughout the Panel Report (not just the findings and recommendations), so that they can not only form their own conclusions, but can also improve the comparative techniques that could provide guidance for the direction of the fusion program.

5.2 Research Directions

In spite of the complexity, the Report suggests generic research directions that can be described fairly simply.

5.2.1 Physics. The Report indicates that high β_e and low χ_E are the appropriate physics directions to maximize the economic potential for fusion. Success will allow the production of wall loadings which result in both a physics and a technological challenge. The physics challenge is to learn how to control the plasma edge conditions so that a technological solution is practical.

5.2.2 Technology. Economic considerations motivate the utilization of higher thermal and neutron wall loadings, and high power densities in the blanket. Integrated designs and materials for the blankets, first wall, and edge control components need to be developed to withstand these high power density fusion conditions.

5.3 The Potential of Magnetic Fusion

Achieving the minimum target of P_m = 100 kWe/tonne would correspond approximately to simultaneously attaining β_e = 10%, χ_E = 0.5, and $\langle I_w \rangle$ = 5 MW/m². Reaching these conditions provides a significant physics and technological challenge to the program. These new requirements imposed by economics may cause some discouragement if the more familiar $n\tau_e$ and temperature requirements for ignition were all one thought was required for the success of fusion. My own view is that there are a wide variety of potential solutions and, considering the remarkable progress in fusion in the past, the probability is good that these target values can be achieved and probably by more than one approach.

While meeting the minimum target for P_m is projected to result in an economically competitive COE, it may not be sufficient to encourage the support and funding for the development phase of fusion. The capital costs and timescale for development steps may appear unacceptably large, particularly if the present governmental view persists that there is no urgency to develop fusion. Concepts which have the potential for substantially exceeding the 100 kWe/tonne threshold are less well developed scientifically at the present time, but may provide the only economically viable development path. Because of this possibility, I believe that an increased emphasis needs to be placed on those concepts that have the potential to substantially exceed the threshold, and that the major effort for all fusion concepts should be to at least meet the threshold conditions.

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