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Prospects for attractive fusion power systems

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As one of the alternative sources of energy for the future, fusion power must demonstrate that it can be a safe, clean and economically attractive option in a diverse and competitive energy marketplace. Conceptual power-plant design studies for both magnetic- and inertial-confinement approaches allows one to translate commercial requirements into design features that must be met if fusion is to play a role in the world's energy mix. As a new technology in the energy marketplace, fusion must have advantages to offset the inherent technical risk of a new technology in order to be accepted. Fusion electricity should have a competitive cost and fusion power plants should achieve a high degree of availability and reliability. Realization of the full safety and environmental potential of fusion will help fusion to achieve a large advantage over other sources of electricity.

Progress in the physics of the magnetic fusion power plant, technology and design is described for tokamaks and alternative magnetic-confinement systems. Recent research in this area shows that potential safety and environmental attributes of fusion can be realized by using low-activation material and care in design. The projected economic prospects show that fusion will be capital intensive and the trends are towards higher power density and higher-performance systems in order to enhance the economic competitiveness of fusion. In addition, alternative confinement approaches may offer substantial economic and operational benefits, although their physics basis is much less developed. Fusion power technologies are far less advanced than plasma technologies, since the latter have evolved in conjunction with large fusion experiments. And yet the design, material choices and performance of plasma-facing and nuclear components are the dominant factors in arriving at an attractive power plant. Fusion power technologies are reviewed, and the R&D needed will be assessed in the context of the world's existing programmes.

Keywords: fusion power plants; fusion technologies; tokamaks; alternative magnetic confinement

1. Introduction

Controlled fusion is one of the long-term sources of energy available to humanity. One of the enduring visions for fusion research is to provide a clean and essentially limitless supply of energy. However, as one of the alternative sources of energy for the future, fusion power will be required to demonstrate that it can be a safe, clean and economically attractive option in an increasingly diverse and competitive energy marketplace. Conceptual power-plant design studies for both magnetic- and inertial-confinement approaches allows one to translate commercial requirements (summarized in § 2) to design features that must be met if fusion is to play a role in the

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world's energy mix. In addition, conceptual design studies help guide fusion R&D by examining extrapolation of present theoretical and experimental data, as well as proposing innovative design solutions.

In this paper, we review the status of magnetic-fusion power-plant design studies and evaluate the continued progress in international fusion research that will lead to a commercially desirable end product. The status of inertial-fusion power-plant design studies are discussed in another paper in these proceedings (Bangerter, this issue). The plasma physics aspects of various magnetic fusion concepts have been discussed in other papers in this discussion meeting and are not repeated here (Aymar, Hawryluk, Keilhacker, Robinson, Putvinski *et al*., all this issue). Section 3 reviews fusion power technology systems that surround the plasma and recover the fusion energy. In § 4, fusion power plants based on the tokamak concept are discussed, and § 5 reviews the potential advantages and R&D issues for alternative magnetic-confinement concepts. Summary and conclusions are given in § 6.

In reviewing the international activities in conceptual fusion power-plant design, two important points should be noted.

1. While the generic goals of enhanced safety and environmental features, operational reliability and availability, and economics are shared by fusion researchers worldwide, quantitative measures for these goals differ significantly because of the different socio-economic conditions, licensing regulations, etc., as well as different research funding priorities. For example, Japanese and other Pacific Asian countries are rather poor in energy resources. Thus, Japanese studies usually emphasize small extrapolation from the present data, and more recently, acceptable economics. On the other hand, European studies in recent years have placed a great emphasis on enhanced safety and on the environmental features of fusion power plants. In the US, fusion power should compete with abundant and inexpensive domestic energy resources and, thus, US studies emphasize both economic, and enhanced safety and environmental features more aggressively than other countries. It is not surprising that US studies typically assume a larger extrapolation in the present database compared with the rest of the international community.

2. Fusion power plants are complex, and a self-consistent analysis of all power-plant systems—a substantial effort—is essential in order to arrive at the proper conclusions. Coordinated activities in the conceptual design of fusion power plants also vary substantially around the world. In Europe, many conceptual design studies were performed in the Culham Laboratories during the 1970s and 1980s, but, in recent years, research has been more focused on the assessment of the potential of fusion power plants, such as the Safety and Environmental Assessment of Fusion Power (SEAFP) study (Raeder *et al*. 1995), and detailed studies of some power-plant subsystems, such as the EU DEMO blanket studies (Dalle Donne *et al*. 1995; Giancarli *et al*. 1995), or recent work on physics optimizations for stellarator power-plant designs (Wobig *et al*. 1998, and references therein). A recent study of the Spherical Tokamak power plant is also on-going (Robinson 1998). Since the Steady State Tokamak Reactor (SSTR) study (Seki *et al*. 1991), Japanese effort in tokamak power-plant designs has mainly focused on studies to improve various aspects of the SSTR design. A detailed study of helical fusion reactors has recently been started by Japanese

universities under the auspices of the Japan National Institute for Fusion Studies (NIFS). In the US, most of the conceptual design research is performed by a national team: the ARIES Team. This team comprises scientists from several national laboratories, universities and industries, and is led by the University of California, San Diego. Over the past 10 years, the ARIES Team's research has included the TITAN, ARIES and SPPS designs.

Detailed information on present worldwide research on conceptual power-plant design can be found in papers of the Proceedings of the 1998 International Atomic Energy Agency (IAEA) Technical Committee Meeting on Fusion Power Plant Design, which is to be published in the Journal of Fusion Engineering and Design in 1999.

2. Requirements for commercial fusion power

The requirements for the commercial success of fusion power have been derived, and are based on discussion and advice from US electric utilities and industry (Kaslow *et al*. 1994; Najmabadi *et al*. 1997*a*). These criteria can be divided into three categories: gaining public acceptance (safety and environmental features); operational reliability and availability; and economics. Gaining public acceptance through safety and environmental attractiveness is essential. It can be achieved by ensuring that the consequences of the most severe accidents are minimal, e.g. there should be no need for a public evacuation following severe accidents. Further, the waste produced by the power plant should be disposable with a reasonable cost and time period, e.g. plants should generate no higher than low-level radioactive waste. These attributes can only be achieved through the use of low-activation material and care in design. The fact that operation of fusion power plants has no atmospheric impact is also a powerful and positive attribute in light of the Rio and Kyoto summits.

It should be noted that the maximization of safety and environmental attractiveness has been a major driver, for the past few decades, in conceptual design studies such as ARIES (Najmabadi *et al*. 1991, 1993, 1997*b*; Conn *et al*. 1991) and SEAFP (Raeder *et al*. 1995). It is also illuminating to note the differences in the quantitative measures used in these studies. In the waste-disposal area, the US Federal Code of Regulations defines categories for low-level waste and their respective repository, i.e. classes A, B and C low-level waste, with class A representing the lowest-level waste. Therefore, ARIES designs have aimed at achieving, at least, a class C categorization under the US Federal Code of Regulations with ARIES-RS achieving a class A rating. The European community does not have regulations in regards to low-level waste. So the aim has been mainly to limit the half-life of the waste to several hundreds years as well as minimizing the amount of waste that should be disposed of in geological repository. In terms of safety, both European and US studies aim at designs that do not require an evacuation plan, i.e. a maximum dose of about 1 rem at the site boundary under the most severe accident. However, US studies tend to emphasize achieving this goal without the need for a confinement building similar to those used for fission power stations. As such, US studies tend to favour very-low-activation material.

Operational reliability and high availability are essential for the success of any commercial product. Today's fusion experiments, by their charter, are not intended to provide detailed engineering data in this regard to support design, construction and operation of a power plant; the International Thermonuclear Experimental Reactor (ITER) is the first device to do so. Conceptual design studies can show schemes for rapid maintenance of the fusion core (the so-called mean time to repair). For example, the ARIES-RS power plant, described in § 3, is designed such that the fusion power core can be replaced in one month during scheduled outages (Tillack *et al*. 1997). Reliability data for various components, however, are essential to estimate and improve the mean time between failures and unscheduled outages. These requirements should be addressed in the development path of fusion power.

Finally, fusion must have a cost advantage to offset the inherent technical risk of a new technology or it will never be widely endorsed. The cost here reflects a life-cycle cost including delays due to licensing and public opposition, cost due to decommissioning and waste disposal, carbon taxes, etc. Large uncertainties exist in forecasts of supply and demand for energy end-use, in environmental conditions (such as global warming, acid rain and waste disposal), in variations among national regulations and needs, and in characteristics of future energy sources. Nevertheless, it is important to make the effort and arrive at goals and requirements for fusion power cost, as the potential safety and environmental advantages of fusion will be offset if the technology proves to be too costly or complex to implement. Definite cost goals are not usually stated in European or Japanese studies. Typically, the aim is to have an acceptable economics (usually defined as 1.5 times that of fission power). In the US, the cost-of-electricity goal of 6.5 cents kWh^{-1} and requirement of 8 cents kWh^{-1} were adopted for the ARIES-RS tokamak study based on the estimated cost of competitive sources of electricity at about 2040 (Miller 1995). These cost goals were arrived at using future increases in the price of fossil fuel in the US as projected by the US Department of Energy's Annual Energy Outlook report, 1996 (US DOE 1996). A macro-economic study of the potential contribution of fusion to the US energy market has also arrived at a target cost of 6 cents kWh^{-1} (Clarke 1995). While these cost requirements represent a reasonable starting point, further effort in reducing the cost is essential to ensure successful introduction of fusion. For example, the US Department of Energy's Annual Energy Outlook reports for 1997 and 1998 (US DOE 1997, 1998) have reduced their projected increase in the cost of fossil fuel. It should be noted that the above two studies did not consider fission power plants. As an indicator, studies of advanced fission power plants in the US indicate a cost of electricity of about 5 cents kWh^{-1}, which assume 'streamlined' licensing and do not include the cost of disposal of fission waste.

3. Fusion power technologies

The wall of the plasma chamber is the first material boundary that faces the plasma (see figure 1). This 'first wall' is subjected to heating by the electromagnetic radiation from the plasma (mainly X-rays), to erosion by flux of charged particles diffusing from the plasma and fast neutral atoms produced by charge-exchange processes in the plasma, and to radiation damage caused by energetic neutrons produced by the fusion reactions. In a fusion power plant, the plasma chamber is surrounded by a blanket that recovers the fusion energy. In deuterium–tritium-fuelled (D–T-fuelled) power plants, the blanket must also breed tritium since this isotope is not found naturally. The number of tritium atoms produced in the blanket for each D–T neutron is referred to as the tritium breeding ratio (TBR). Since each fusion reaction

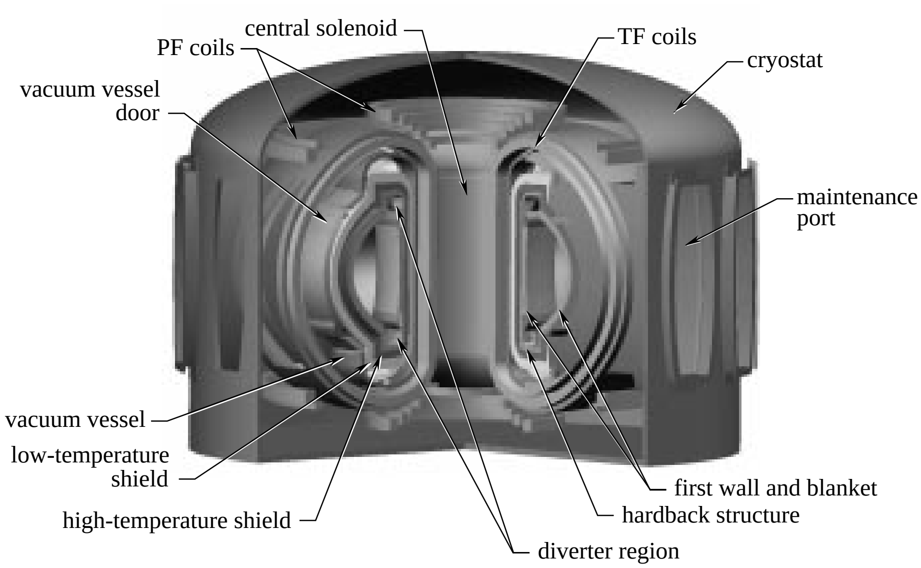

Figure 1. The cross-section of the ARIES-RS tokamak fusion power plant.

uses one tritium and generates one neutron, a TBR of 1 or greater is required for tritium self-sufficiency. Tritium breeding is achieved by including lithium or a lithium compound in the blanket and using the reactions:

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + {}^{4}\mathrm{He}, \tag{3.1}$$

$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + {}^{4}\mathrm{He} + \mathrm{n}. \tag{3.2}$$

Most of the fusion neutrons that enter the blanket are captured by lithium in order to breed tritium. (This also minimizes activation of power-plant components.) A small portion of neutrons, however, are absorbed by the structure and the coolant. In some designs, the extra neutron produced by the ^{7}Li reaction is sufficient to achieve a TBR of 1. In other designs, a neutron multiplier such as Be or Pb is added to the blanket to assure tritium self-sufficiency. Several blanket designs are discussed below. Blankets are typically 0.8–1 m thick and attenuate the neutron flux by about two orders of magnitude.

The neutron and radiation flux should be reduced by another six orders of magnitude for the safety of workers. In concepts that use superconducting magnets, a metallic shield is located behind the blanket (typically 0.5–1 m thick), which reduces the neutron flux by four orders of magnitude to allow plant-life operation for these magnets. A radiological shield (typically made of concrete) is then placed beyond the coils.

Fusion power technologies encompass the first-wall and other plasma-facing components, blanket, shield and other systems needed for recovery of fusion energy. These technologies are far less advanced than plasma technologies as the latter have evolved in conjunction with large experiments. And yet the design, material choices and performance of plasma-facing and nuclear components are the dominant factors in arriving at an attractive power plant. Material choices are most critical for fusion power technologies. The structural material should withstand radiation damage by neutrons. Economic competitiveness requires a high thermal conversion efficiency

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and, therefore, a high-temperature operation for first-wall and blanket material. Achieving the attractive safety and environmental features of fusion requires that the fusion-core components be constructed with materials with a low level of induced activation, the 'low-activation material'. During the 1970s, most of the research effort on the structural material was focused on stainless steels because of the experience in the fission industry. During the 1980s, research was shifted to low-activation material. Primary candidates in this category are low-activation ferritic steels, vanadium alloys and SiC–SiC composites. The status of fusion material R&D is summarized by Ehrlich in this issue. Here, we review fusion power-plant blanket designs based on these structural materials.

New reduced-activation variants of ferritic/martinisic steel appear capable of meeting safety and waste-disposal requirements, and are pursued in some parts of the world as the primary, or sometimes only, option for near-term R&D. Many coolant options are available for ferritic steel blankets, such as water, He gas or liquid metal (e.g. PbLi). An example of a ferritic steel blanket is the European dual-coolant concept (Giancarli *et al*. 1995). Another example is the recent blanket design for ARIES-ST (Najmabadi *et al*. 1998), which is a variant of the European dual-coolant concept (shown in figure 2). The ARIES-ST blanket has a box-like geometry. The ferritic steel walls (including the first wall) are cooled by He gas, which is fed through plenua at the back of the blanket. The tritium breeder is the lithium eutectic $Li_{83}Pb_{17}$, which is also circulated as a coolant since most of the fusion neutron energy is deposited in LiPb. The maximum operating temperature of ferritic steels is predicted to be 550 °C. In order to raise the coolant (LiPb) temperature above this value and increase the thermal energy conversion efficiency, thin layers of SiC are inserted between the LiPb breeder and the ferritic steel walls. Analysis indicates that this technique allows a coolant exit temperature of 700 °C for LiPb, and an overall (including both He and LiPb coolant loops) thermal efficiency of 45%.

Vanadium alloys have the potential for improved thermomechanical properties, safety advantages due to lower afterheat and, possibly, longer lifetimes compared to ferritic/martinisic steels. The use of vanadium, however, restricts the use of some materials for coolant and breeder due to compatibility. The best vanadium blanket concept uses liquid lithium as both the breeder and the coolant. A major design issue for Li/V blankets is magnetohydrodynamic (MHD) forces exerted on liquid lithium flowing across the magnetic field. Most magnetic-confinement concepts require the use of an insulating coating to reduce the MHD forces. An example of such a blanket design is shown in figure 3. This blanket also has a box-like geometry with the lithium coolant flowing in the poloidal direction. The first-wall coolant is passed through the back of the blanket and is superheated in order to achieve a high coolant outlet temperature of 610 °C and a gross thermal efficiency of 46%.

Silicon-carbide (SiC) fibre-reinforced SiC composites have a projected allowable temperature capability of over 1000 °C and, therefore, allow for a high thermal conversion efficiency. This material also has excellent safety characteristics because it has the lowest afterheat compared to steels and vanadium. The preferred coolant for this type of blanket is high-pressure He. Figure 4 shows the cross-section of a typical SiC composite-based blanket from the ARIES-IV design (Najmabadi *et al*. 1993). In this blanket, pebble beds of ceramic tritium breeder (Li_2O) and neutron multiplier (Be) are located between SiC-composite tube sheets, which carry the high-pressure helium coolant. A variant of this blanket design (Najmabadi *et al*. 1997*a*)

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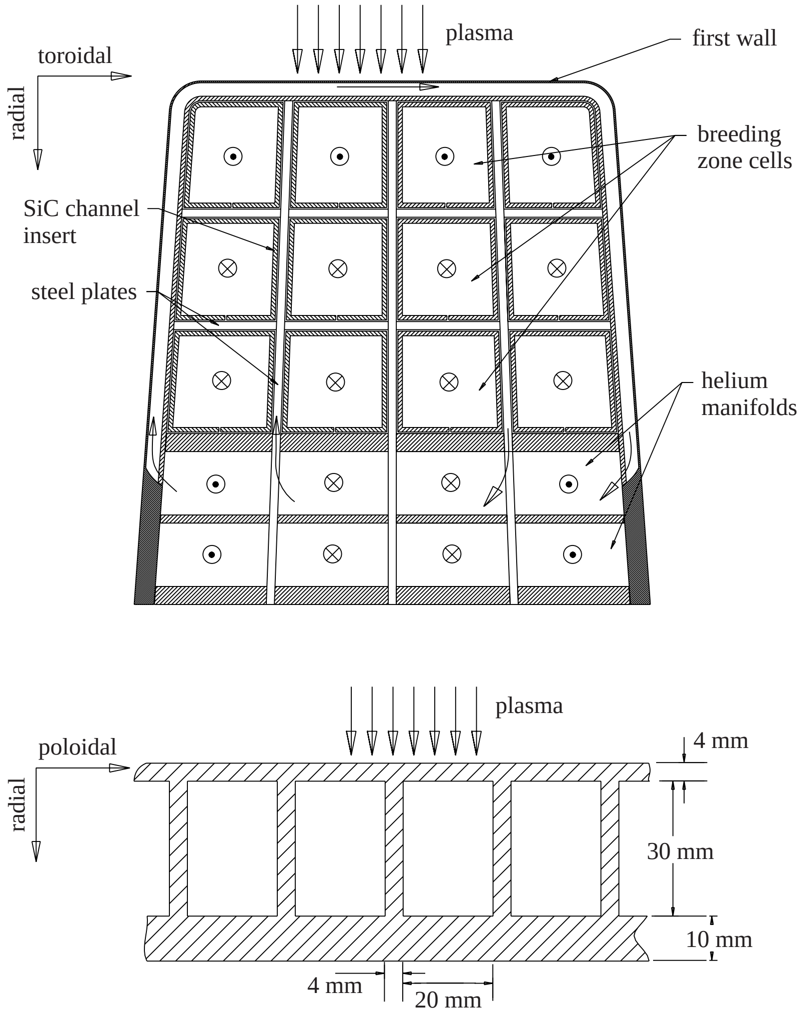

Figure 2. Cross-section of the ARIES-ST blanket, which is a variation of the European dual-coolant concept. The ferritic steel walls (including the first wall) are cooled by He gas, which is fed through plenua at the back of the blanket. The tritium breeder is the lithium eutectic $Li_{83}Pb_{17}$, which is also circulated as a coolant. Thin layers of SiC are inserted between the LiPb breeder and the ferritic steel walls in order to raise the LiPb outlet temperature above the maximum operating temperature of ferritic steels.

uses 12 MPa helium coolant to achieve a coolant outlet temperature of 950 °C and a gross thermal conversion efficiency of 55%. An alternative design is the European TAURO blanket using LiPb as the breeder (Perez *et al*. 1995).

4. Tokamak power plants

In recent years, tokamaks have been the focus of worldwide fusion research, having achieved the most impressive confinement performance results. The tokamak magnetic topology is generated by external toroidal-field coils (see figure 1) and by the toroidal current flowing in the plasma. In present-day experiments that are

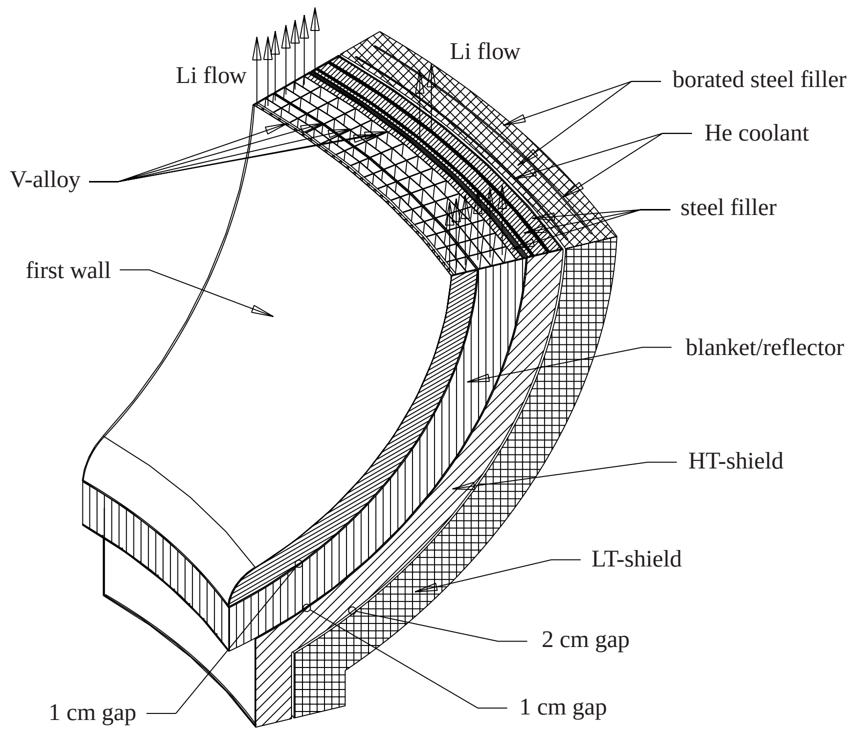

Figure 3. Cross-section of the ARIES-RS blanket. The lithium coolant and breeder flow in the poloidal direction in a box-like structure made of vanadium alloys. An insulating coating is used to reduce the MHD forces. The first-wall coolant is passed through the back of the blanket and is superheated in order to achieve a high coolant outlet temperature.

pulsed, the plasma current is generated by magnetic induction (transformer action). For steady-state operation, the tokamak plasma current must be sustained by other means. Current can be driven in the plasma by using neutral particle beams or microwaves. However, a steady-state tokamak power plant, driven solely by neutral beams or microwaves would require a large recirculating power because of the intrinsic low efficiency of these schemes. Theoretical studies predict that in a sufficiently hot plasma, the radial gradient of plasma pressure and dynamics of plasma flow on the flux surfaces combine to produce self-driven (bootstrap) current. Existence of a bootstrap current has been experimentally confirmed. In the late 1980s, steady-state operation through optimization of the plasma MHD equilibrium and stability to achieve a high bootstrap current was first proposed in the ARIES (Najmabadi *et al*. 1991; Conn *et al*. 1991) and SSTR (Seki *et al*. 1991) studies simultaneously and independently. Detailed analysis showed that through operation at low current (*ca.* 10 MA) and high poloidal beta at a moderately high aspect ratio (*ca.* 4), a bootstrap-current fraction (ratio of bootstrap current to the plasma current) of about 70% can be achieved. This will lead to current-drive powers of about 100 MW delivered to the plasma (by neutral beams or microwaves) for a typical 1000 MW_e power plant.

The above trade-off between MHD and current drive resulted in research into new 'advanced' tokamak modes during the last ten years. Furthermore, improve-

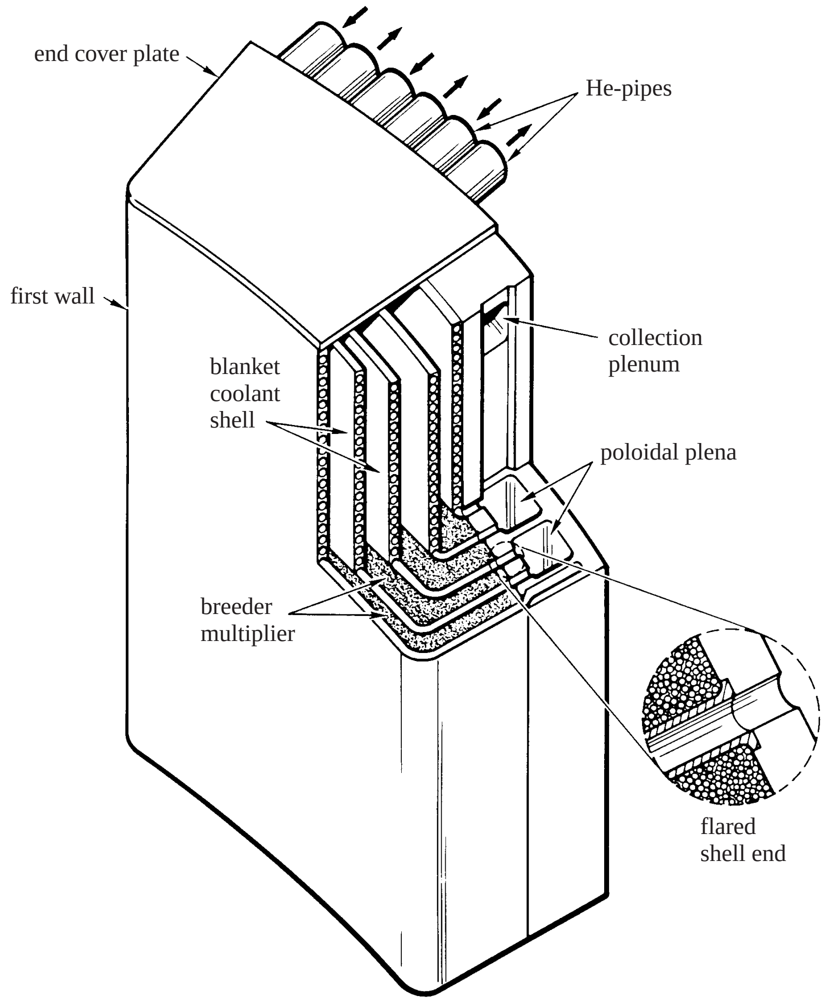

Figure 4. Cross-section of the ARIES-IV blanket. Pebble beds of ceramic tritium breeder (Li_2O) and neutron multiplier (Be) are located between SiC-composite tube sheets, which carry the high-pressure helium coolant. A variant of this blanket design (Najmabadi *et al*. 1997*a*) uses 12 MPa helium coolant to achieve a coolant outlet temperature of 950 °C and a gross thermal conversion efficiency of 55%.

ment in plasma performance (higher bootstrap fraction, higher plasma beta) has been achieved. The most-promising advanced-tokamak mode is the reversed magnetic shear (Ozeki *et al*. 1993; Kessel *et al*. 1994; Jardin *et al*. 1997), and intense experimental activity is on-going in large tokamaks worldwide. An example of a fusion power-plant based on the reversed magnetic shear mode is ARIES-RS, a 1000 MW_e conceptual power-plant design (Najmabadi *et al*. 1997*a*, *b*). The major parameters of ARIES-RS are given in table 1, and a cross-section of this power plant is shown in figure 1.

The ARIES-RS plasma is optimized to achieve a high plasma pressure and a

Table 1. *Major parameters of ARIES-RS*

aspect ratio	4
major radius (m)	5.52
minor radius (m)	1.38
plasma vertical elongation (X-point)	1.70
plasma current (MA)	11.32
bootstrap-current fraction	0.88
current-drive power (MW)	81
peak magnetic field on the coils (T)	16
toroidal β	0.05
average neutron wall load (MW m^{-2})	3.96
primary coolant and breeder	natural lithium
structural materials	vanadium and steel
coolant inlet temperature (°C)	330
coolant outlet temperature (°C)	610
fusion power (MW)	2170
total thermal power (MW)	2620
net electric power (MW)	1000
gross thermal conversion efficiency	0.46
net plant efficiency	0.38
recirculating power fraction	0.17
cost of electricity (cents kWh^{-1})	7.6

high bootstrap-current fraction (*ca.* 90%) that is very well aligned with the required equilibrium current-density profile. The current-drive analysis showed that about 80 MW of current-drive power is necessary for steady-state operation. This design uses a lithium-cooled blanket with a vanadium structure (see figure 3), which achieves a high thermal conversion efficiency of 46% (using 610 °C coolant outlet temperature and a Rankine steam cycle). Use of vanadium in the high-temperature zones provides sufficiently low levels of afterheat that worst-case loss-of-coolant accidents can be shown to result in a small release of radionuclides (below 1 rem at site boundary), well below the values specified by standards and regulations. The blanket is made of sectors and rapid removal of full sectors is provided through large horizontal ports (see figure 1), followed by disassembly in the hot cells during plant operation (Tillack *et al.* 1997). The simple blanket design with a small number of cooling channels and low mechanical stresses in the structure provides a good basis for high reliability.

5. Power plants based on alternative concepts

The economic potential of the tokamak can be improved through efficient use of the magnetic field and/or a reduction in the power required to maintain the plasma current. Alternative toroidal magnetic-confinement concepts such as stellarators, reversed-field pinches and spherical tokamaks have unique advantages in this regard (Robinson 1998, and this issue). Tokamak operation at a low aspect ratio (low aspect ratio or spherical tokamak) is one approach to achieving high plasma (and a high bootstrap-current fraction). Unfortunately, the low aspect ratio (typically 1.2–1.6) inhibits the use of superconducting coils as there is not enough space for a thick shield around the centre column. Water-cooled copper coils are usually used for this concept and the engineering design of this centre column (inboard return leg of the toroidal-field coils) is challenging. Resistive losses in the centre column dominate the recirculating power in a spherical-tokamak power plant and drive the system optimization. The spherical tokamak is currently pursued vigorously around the world, with two 1 MA class devices under construction in the UK and the US. In particular, because a high plasma temperature can be achieved in small and inexpensive spherical tokamak devices, this concept might be ideal for fusion development.

The stellarator magnetic topology is similar to that of a tokamak, however, the confining magnetic field is produced only by coils outside the plasma. Since there is no need for plasma current, stellarators are inherently steady-state and require no current-drive power. In addition, certain classes of MHD stability associated with the plasma current are avoided. Recent theoretical and experimental achievements have resulted in the construction of two large stellarator experiments, the large helical device (LHD) in Japan and W7-X in Germany. Both devices use superconducting magnets. Stellarators require external coils with complicated geometry. Because the dipole, quadruple and higher-order fields drop off rapidly away from a coil, the space between the coils and the plasma (which is occupied by the first wall, blanket and shield in a power plant) is a critical parameter in stellarator design. Research into more-compact (smaller-aspect-ratio) stellarator configurations promises further reduction in size. An example of research in this direction is the recent SSPS stellarator power-plant study (Miller *et al*. 1997).

The reversed-field pinch (RFP) magnetic topology consists of nested flux surfaces similar to those of a tokamak. However, in an RFP, most of the confining toroidal field is generated by the toroidal plasma current through a dynamo action (Taylor 1974; Bodin *et al*. 1986). As a result, only small low-field toroidal-field coils are required. RFPs are inherently compact and plasma β values needed for power plants have been achieved experimentally. The plasma current in a reversed-field pinch should be sustained for steady-state operation, similar to a tokamak. Efficient current-drive techniques based on helicity injection, such as oscillating-field current drive (Najmabadi *et al*. 1989, 1990), have been proposed for RFPs that use the dynamo action. (The natural plasma profiles in an RFP prohibit a large bootstrap-current fraction.) The TITAN RFP power-plant study (Najmabadi *et al*. 1989, 1990) has shown that compact RFP power plants with a high wall loading, low-field copper coils, and a modest recirculating power fraction are possible. The major plasma physics issue for RFP is plasma transport and energy confinement, as the dynamo action that is responsible for the maintenance of the RFP magnetic configuration increases the plasma transport substantially. Research is now aimed at reducing the dynamo action through plasma-profile control.

6. Summary and conclusions

Progress in fusion power-plant physics, technology and design is described for tokamaks and alternative magnetic-confinement systems. A set of requirements for success of commercial fusion was described. While the specific requirements for fusion may vary in different countries, the underlying theme of a safe clean energy source with a competitive cost is a universal requirement for fusion. Several key factors are known to be important, e.g. capital cost, availability, thermal conversion efficiency, power density, and activation of the fusion core. Fusion electricity should have a

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competitive cost and fusion power plants should achieve a high degree of availability and reliability. Realization of the full safety and environmental potential of fusion will help fusion to achieve a large advantage over other sources of electricity. Recent research in this area has shown that potential safety and environmental attributes of fusion can be realized by using low-activation material and by taking care in design.

The projected economic prospects show that fusion will be capital intensive, and the trends are towards higher power density and higher-performance systems in order to enhance the economic competitiveness of fusion. For example, ten years ago, the 'credible' vision of a tokamak power plant was a pulsed device. Research in advanced tokamaks now projects steady-state power plants with a substantial reduction in size and about a factor of two reduction in the cost of electricity. Alternative confinement approaches may offer further economic and operational benefits, although their physics basis is much less developed.

Fusion power technologies are far less advanced than enabling technologies for fusion plasma experiments, since the latter have evolved in conjunction with large fusion experiments. And yet the design, material choices, and performance of plasma-facing and nuclear components are the dominant factors in arriving at an attractive power plant. Developing technologies for the fusion power core and power plant requires a substantial increase in efforts. A more coordinated and intensive worldwide programme in fusion technology aimed clearly at developing attractive fusion power systems is an essential element for a successful fusion programme.

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Discussion

I. Cook (*UKAEA Fusion, Culham Science Centre, Oxfordshire, UK*). Professor Najmabadi made a point that fusion, as a new technology, must be financially attractive in order to provide an incentive for it to be sucked into the market. But fusion has no CO_2 production, no real severe accidents, and only low-level waste. In the future, this might be enough if the costs are reasonable (even if not strictly competitive). In addition, most of the cost of electricity to the consumer is in distribution;

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electricity is only a small part of the spending of households and firms; only 20% of a modern economy is manufacturing. So, is he not setting himself an impossible, and unnecessary, target?

F. Najmabadi. Fifty years from now, the cost, and the energy and environmental conditions may be very different. However, we have to sell the programme now. This means that we need to be comparable with present-day costs and hope that the safety and environmental benefits of fusion will carry the day.

K. Lackner (*Tokamak Physics Division, Garching, Germany*). Did any of the alternatives to the tokamak lead to a significantly different cost of electricity?

F. Najmabadi. No. A major portion of the cost is for components outside of the fusion core. As such advanced tokamaks (reversed shear), Spherical Tokamaks, etc., appear to have comparable costs.

R. J. Bickerton (*Cumnor, Oxfordshire, UK*). Do the estimates for different power plants include different materials development costs?

F. Najmabadi. The different designs imply a first-wall neutron irradiation difference of only a factor of two, with unchanged thermomechanical design criteria.

R. Bullough (*Reading, UK*). There could be a big difference in development costs between your designs with different wall loadings.

F. Najmabadi. Costs reported here are for a tenth-of-a-kind commercial power plant and does not include development cost.

C. Gormezano (*JET Joint Undertaking, UK*). What advanced technology can help fusion?

F. Najmabadi. An option I would like to look at would be high-temperature superconductors that can allow for high field and/or simpler designs. An example is bismuth compounds, which have a higher field capability than Nb_3Sn when operated at less than 10 K.

J. Sheffield (*Energy Technology Programs, Oak Ridge National Laboratory and the Joint Institute for Energy and the Environment, University of Tennessee, USA*). Dr Gormezano might like to consider high-temperature superconductivity using yttrium–barium–copper–oxide compounds at 700 K, which have good properties at high fields.